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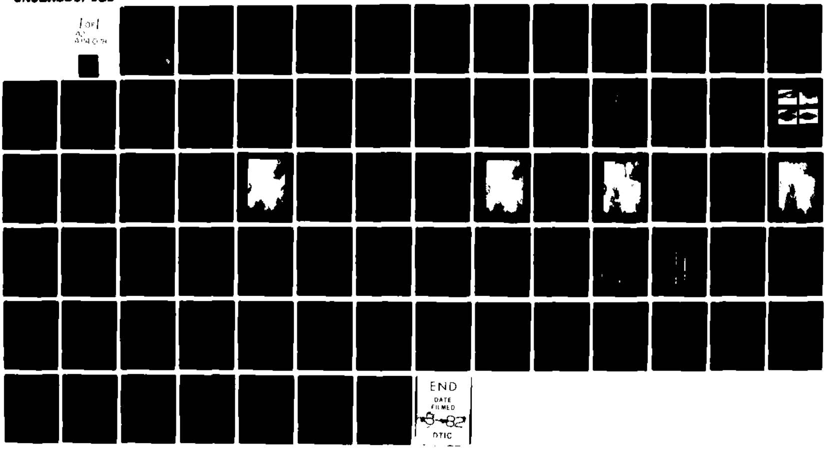

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CORAL CRATERING PHENOMENOLOGY

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31 October 1980

Topical Report for Period 1 May 1977—31 October 1980

CONTRACT No. DNA 001-79-C-0305

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DNA 5813T	2. GOVT ACCESSION NO. AD-A114078	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CORAL CRATERING PHENOMENOLOGY		5. TYPE OF REPORT & PERIOD COVERED Topical Report for Period 1 May 77—31 Oct 80
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert L. LaFrenz		8. CONTRACT OR GRANT NUMBER(s) DNA 001-79-C-0305
9. PERFORMING ORGANIZATION NAME AND ADDRESS Systems, Science and Software P.O. Box 1620 La Jolla, CA 92038		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Subtask Y99QAXSA002-22
11. CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency Washington, D.C. 20305		12. REPORT DATE 31 October 1980
		13. NUMBER OF PAGES 70
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This work sponsored by the Defense Nuclear Agency under RDT&E RMSS Code B344079464 Y99QAXSA00222 H2590D.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cratering efficiency, explosive excavation; coral; Pacific Proving Ground; craters; nuclear surface burst; high explosive; crushing; compaction; saucer-shaped craters; ejecta; crater.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report utilizes the results of Project Tugboat, a high-explosive, optimum depth-of-burial project done in coral overlaid with water to help explain the formation process of the Pacific Proving Grounds (PPG) nuclear surface burst craters. The craters produced during Project Tugboat were wide, flat, and saucer-shaped. The volume was approximately four times larger than contemplated in the design based upon continental experience, and apparently came

20. ABSTRACT (Continued)

entirely from crushing, compaction, and settling of the coral. Included are colored pictures from an aerial movie showing initially a conventional throw-out crater surrounded by a circular area of obviously crushed but still relatively intact coral. Pictures from later movie frames show the crushed coral beyond the ejecta crater collapsing and flowing into the deeper center ejecta crater. There was no ejecta material found above the original ocean bottom elevation, indicating that the entire final volume had to come from crushing, compaction, and consolidation of the in situ material.

It is conjectured that the feature of the wet coral sites responsible for their characteristic flat, saucer-shaped craters is the large, water-filled macroporosity of the highly permeable, brittle coral matrix. This matrix is broken by the passage of the shock, which could be induced either by direct coupling from a buried charge or air blast-induced from a surface detonation. An analysis of the craters at the PPG, based on the information gained from Project Tugboat, led to the following conclusions:

- Crushing, compaction, and settling of the coral by the ground motion resulting from direct energy coupling and the high-pressure air blast could have formed the nuclear surface-burst craters at PPG.

- Flat, saucer-shaped craters are due primarily to the physical properties of the wet coral medium. The large crater volumes per ton of explosive are due to the large, water-filled macroporosity of the highly permeable, brittle coral matrix.

- The shape and volume of the apparent PPG craters are not related to the throw-out cratering phenomenon.

- Calculational techniques based on the throw-out approach to cratering and dry-land cratering experience should not be expected to replicate the PPG results.

- The average of 3.7 m^3/ton (130 ft^3/ton) cratering efficiency for the PPG craters equates to approximately 0.93 m^3/ton (32 ft^3/ton) for craters in equivalent strength dry-land material, if the same volume ratio for high-explosive cratering (coral) overlaid with water to equivalent strength material on dry land holds for nuclear, surface-burst results.

PREFACE

The constructive comments of Dr. Kedar D. Pyatt, Jr., Chief Scientist at Systems, Science and Software, are appreciated in the preparation of this report.

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SECTION 1

INTRODUCTION

This report uses empirical results from a cratering-type excavation project in coral as the basis for an alternative interpretation of the important processes in the formation of the Pacific Proving Grounds (PPG) nuclear, surface-burst craters. The empirical results are from a large, chemical, high-explosive harbor project done in Hawaii in 1970. The harbor excavation project, called Project Tugboat (Day 1972), was done to demonstrate the feasibility of explosive excavation as a construction technique and to model a nuclear explosive excavation project as part of the Plowshare* Program.

The analysis and comparisons in this report provide an empirical justification for the interpretation of the difference between the observed nuclear surface-burst cratering efficiency from the PPG craters and the predicted cratering efficiency for nuclear surface bursts over similar strength soil or rock material with no water overburden. In this report, cratering in soil or rock with no water overburden is referred to as continental cratering. The alternative interpretation of the cratering efficiency for the PPG events correlates well with recent calculational efforts.

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* Plowshare was the code name given to the program to develop peaceful uses for nuclear explosives, primarily the excavation of a sea-level "Panama" canal.

The significance of Project Tugboat is that it provided an opportunity to observe the detailed formation process of the wide, flat, saucer-shaped craters which are typical of the PPG tests. As a result of the high-speed aerial photography and other technical programs, it was possible to observe the initial throw-out crater, the subsequent liquefaction and flowing of the material around it, and then the settlement process. Contributing to the ability to observe this formation process were the unique conditions of the site, a saturated material, and water overburden with no consequent dust cloud.

The Tugboat experiments strongly suggest that the crater shapes and sizes observed in the PPG high-yield nuclear tests are due to the physical properties of the medium in which these tests were conducted, i.e., wet coral. It is conjectured that the features of coral sites which are responsible for their characteristic craters are their complete saturation and low density. The low density results from a large, water-filled macroporosity of very high permeability in a brittle coral matrix.

It is proposed that, in the formation of craters in wet coral, the coral matrix is broken by the passage of the strong shock. The collapse of the grain structure in the saturated low density material leads to a separation of grains and an accompanying loss of strength (this process is called liquefaction). In this state, the broken coral should flow easily and is expected to settle and reconsolidate to a state of increased density and reduced porosity.

These effects, flow and settling or reconsolidation, were both observed in the Tugboat event.

1-1 STATEMENT OF THE PROBLEM

The size of the crater and the resulting ground motion from a nuclear surface burst are of critical importance for predicting the survivability of friendly structures as well as for predicting vulnerability of enemy targets. The Defense Nuclear Agency has been attempting for some time to calculate the expected cratering efficiency (volume/yield) for craters from nuclear surface bursts. To date, the calculational efforts have resulted in predictions that are four to ten times smaller than those actually observed at PPG. Recent and projected increases in weapon delivery accuracy and the imminent design requirements for the MX missile system require a resolution of the discrepancy between analytical cratering predictions and the apparent empirical results from the PPG nuclear surface bursts.

1-2 CRATER CALCULATIONS AND EXPERIMENTS

Calculational approaches to predicting cratering efficiency to date have been related to experience gained in both nuclear and chemical high-explosive tests. The nuclear test data available are primarily from the Nevada Test Site (NTS). At NTS, seven nuclear explosive excavation tests were conducted during the 1960's as part of the Plowshare Program (Teller 1968). Most of these nuclear detonations were at or near optimum depth-of-burial and were in materials which differ considerably from those at PPG. Numerous chemical high-explosive (HE) surface-burst experiments have been conducted; however, the physical processes involved in the crater formation following a chemical explosion are a poor simulator of the processes involved following a nuclear detonation. There is no prompt radiation coupling from an HE test. The high pressure induced in the ground by a nuclear event during the early hydrodynamic phase of the interaction cannot be simulated by HE. The initial high air blast overpressure, P > 100 MPa (15,000 psi), in the vicinity of the crater is not reproduced in an HE event. The high air blast overpressures from a nuclear event may be critical in the PPG crater formation process.

It is possible to calculate and predict crater volume and dimensions relatively accurantely for buried nuclear explosions in unsaturated rock and soils with no water overburden (Roddy 1978). Buried and surface-burst HE craters have also been predicted with good results (Roddy 1978). The calculation for a buried explosion results in a displacement or "throw-out" crater with a bowl-shaped cross section, as shown in Figure 1. Although this type of cratering effect is present when detonating an explosive in or over a coral medium, the saturated, highly porous nature of coral produces a final crater bearing little relation to those from continental experience in dry materials. Craters in saturated coral are generally flat and saucer-shaped, with a volume considerably larger than that predicted for continental cratering.

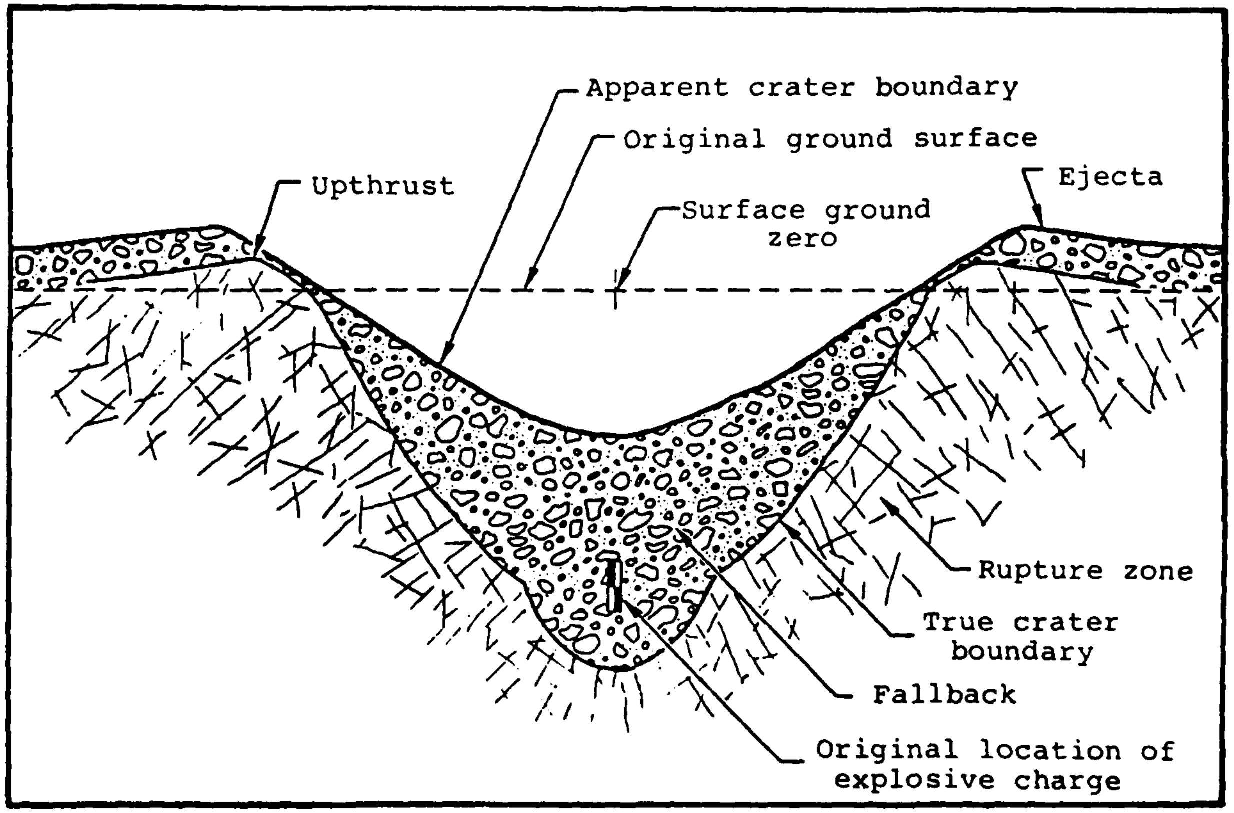


Figure 1. Cross section of a typical crater from a buried explosive charge, showing nomenclature.

SECTION 2

HIGH-EXPLOSIVE HARBOR PROJECT

2-1 BACKGROUND

From 1962 through 1980, the U.S. Army Corps of Engineers (CE) and the Atomic Energy Commission (AEC) conducted a joint research program to develop the basic technology for use of nuclear explosives for construction purposes (Kurtz 1968). The AEC, through the Plowshare Division of the Lawrence Livermore Laboratory at Livermore, California, was responsible for nuclear device development, conduct of the nuclear cratering experiments, and development of nuclear safety and crater size prediction techniques. The U.S. Army Engineer Nuclear Cratering Group (NCG), later called the Explosive Excavation Research Laboratory (EERL), located at Lawrence Livermore Laboratory, conducted the Army portion of the program. The program consisted of chemical high-explosive crater modeling tests, engineering investigation of the craters produced by the chemical and nuclear detonations, the development of project designs and engineering construction data as a basis for nuclear cratering, and later, chemical explosive excavation. In furtherance of this latter technique to demonstrate the feasibility and utility of the general technique of explosive excavation, and to gain technical data to be used in the design of other chemical or nuclear explosive excavation projects, it was decided to perform a major, useful engineering project using the technique. The project chosen was a small boat harbor in Hawaii. It was code-named Project Tugboat (Day 1972).

2-2 PREVIOUS EXPERIENCE

The Nuclear Cratering Group conducted 13 major explosive excavation test series near Fort Peck, Montana, from 1966 through 1969, under the code name Project Pre-Gondola (LaFrenz 1970). The purpose of the experiments was to establish the cratering characteristics of weak and saturated shale, to acquire row-charge cratering experience, and to demonstrate the feasibility of connecting a row crater to a body of water. The clay shale site was initially chosen to provide cratering experience in a material similar to much of the soil type which existed in sections of the routes being considered for an Atlantic-Pacific sea-level canal. The original tests at Fort Peck were designed to model a nuclear test, Gondola, which was canceled. The cratering experience from Fort Peck provided the original design basis for Project Tugboat. The material properties of the clay shale were thought to match those of the coral quite closely.

2-3 HARBOR SITE

Project Tugboat was planned to provide data that could be used in both chemical and nuclear excavation technology and to serve as a useful demonstration project. It was designed to create an entrance channel and a berthing basin for a small boat harbor as part of an authorized U.S. Army Corps of Engineers Civil Works Construction project at Kawaihae, Hawaii. Not only was it to be the first major construction project using explosive excavation, it was to be done in a coral material covered with water, a medium in which no HE cratering experience existed.

The Island of Hawaii, like all of the Hawaiian Islands, was constructed by the geological process of volcanism, and is composed predominantly of basaltic rock. In places along Hawaiian coasts where conditions are favorable, coral reefs have grown. Such conditions exist in the Kawaihae area, so that the basic geologic situation at the Tugboat site was one of a coral reef founded at some depth upon basaltic rock, the latter being continuous with the basalt which forms the adjacent land mass. The ocean bottom at the site was very irregular because of the numerous coral heads, some of which caused variations of as much as 3.66 m (12 ft) within a few meters horizontally. In general, water depths over the coral at the Tugboat site ranged between 1 and 4 m.

The geology of the Tugboat site is essentially that of the coral reef, since the underlying basalt foundation lies at depths greater than any of the explosive detonations and greater than any of the exploratory borings drilled either before or after the shots. Coral is the generic name for biogenic carbonate rocks made by marine animals and plants. It is composed of the limy skeletal materials secreted by numerous species of marine invertebrate animals, and also by symbiotic lime-secreting algae. Collectively these animals and plants form colonies, and an assemblage of these colonies forms a reef. A coral reef is a complicated ecological system, and the limy material shows a complicated variety of structures, even though the structures are all made of the same material, calcium carbonate. Some colonies are massive and dome-like, some are branching and shrub-like, with a fragile skeleton that is easily shattered or broken. The substructure of a visible coral reef represents reef materials that grew in the past. Numerous animals besides the actual coral-formers live in and around the coral reef. On death, the calcareous remains of these organisms (shells, spines, etc.) combine with broken parts of the more fragile coral structures to form calcareous sand and silt, which filter into and partially fill voids in the coral framework. At some time in their geological evolution, reefs and their infilling sediment may, but do not necessarily, become cemented together by deposition of a calcareous cement, resulting in formation of a solid limestone rock.

Longitudinal openings across the surface of a reef, normal to the shore, are a common feature. These "surge channels" occur at semiregular intervals, and have dimensions of a few feet. The floors of such channels are flat or slope gently seaward, and are covered with coral sand. Similar but larger channels occur opposite fresh water springs or the mouths of fresh water streams. The Kawaihae coral reef is typical of the generalized reef described above.

A drilling program was carried out in June and July of 1969 to investigate subsurface conditions at the Project Tugboat site (Day 1972). Fifteen borings were drilled to depths as great as 23.2 m (76 ft) below mean low-low water (MLLW). A combination of splitspoon drive sampling, 0.1 m (4 in) diameter, core drilling, and Denison sampling was used. Some intervals were washed and jetted. Collectively, 210 m (687 ft) (linear) of hole were drilled, of which 93 m (304 ft) were core drilled. All holes required casing to their full depth except for the final drill run or two. From the 93 m (304 ft) in which coring was attempted, 37.5 m (123 ft) of material was recovered (40 percent recovery). Only 2.14 m (7 ft) of core was recovered in lengths of 0.15 m (6 in) or more, and the longest piece recovered was 0.5 m (1.6 ft). The poor core recovery is attributable to the discontinuous nature of the reef structure, and is compatible with results experienced during construction of the Kawaihae deep-draft harbor.

The following is a summary of some of the testing results on the coral cores:

Porosity: Solid intact samples, mean porosity 50 percent ± 13 percent.

These results measure only the porosity of the laboratory samples due to small voids within the coral material. The porosity of the reef would be much greater, since it would be due as well to the macroscopic voids between various coral branches, etc. In fact, all test values are valid only for laboratory samples, not for the reef mass as a whole, because of the open, branching structure of the latter. (In effect, the lab samples are not truly representative of the reef mass as a whole.) The reef mass possesses, by an indeterminate amount, a lower mean strength, lower mean density, and much higher mean porosity than the test values indicate.

Unconfined compressive strength: mean 7.4 MPa (1080 psi)

Bulk density: mean 1.76 ± .13 gm/cm^3

Apparent grain density: mean 2.24 ± .22 gm/cm^3

Unit weight (dry): mean 1.33 ± .21 gm/cm^3

Seismic: A seismic refraction survey was made at the Tugboat site area in May 1969. Six 33.6 m (110 ft) lines were run parallel to the revetment, one 200 m (650 ft) line was run oblique to the revetment, and a 252 m (825 ft) traverse made up of three 83.9 m (275 ft) segments was run oblique to the revetment and along the then-proposed channel alignment. All lines showed low-velocity material at shallow depths, with P-wave velocities in the range of 1535-1830 m/sec (5100-6000 ft/sec) (only slightly above the velocity of water, which is about 1525 m/sec [5000 ft/sec]). This material represents the coral reef. Only the 200 m (650 ft) line effectively explored material deeper than 30.5 m (100 ft) below the ocean floor. This line detected the presence of higher velocity material at about 21.4 m (70 ft) depth, 45.8 m (150 ft) from the revetment, sloping down to 33.6 m (110 ft) depth, 229 m (750 ft) from the revetment. This material had an average velocity of 3248 m/sec (10,650 ft/sec) and was presumed to be the basalt foundation on which the coral reef rests. This higher velocity material was detected only on this one line.

The seismic data suggested considerable lateral variation within the coral. The highest velocity within the coral, 2208 m/sec (7240 ft/sec), was measured along the long axis of a single, continuous coral reef.

2-4 HARBOR DESIGN

The requirements for the harbor were for a 36.6 m (120 ft) wide entrance channel and a berthing basin of at least 5116 m^2 (55,000 ft^2), all at a minimum depth of 3.66 m (12 ft). The original design was done in 1969 and was based on the chemical and nuclear experience to that date. The design was, therefore, predicated on a "throw-out" type of crater, shown in cross secton in Figure 1 and as Curve A of Figure 2. The following were the scale crater dimensions:

DOB = depth-of-burst = 42.7 m (140 ft)/$kt^{1/3.4}$

R_a = apparent crater radius
= 61 m (200 ft)/$kt^{1/3.4}$

D_a = apparent crater depth
= 27.5 m (90 ft)/$kt^{1/3.4}$

H_{a1} = average crater lip height = 0.5 D_a

The preliminary design based on these scaled crater dimensions utilized ten each, 10-ton charges to provide an entrance channel 183 m (600 ft) long and 36.6 m (120 ft) wide and ten each, 10-ton charges in two rows of five each to provide a berthing basin 100.7 m (330 ft) long and 54.9 m (180 ft) wide. The actual depth-of-burst and crater dimensions used in this design were:

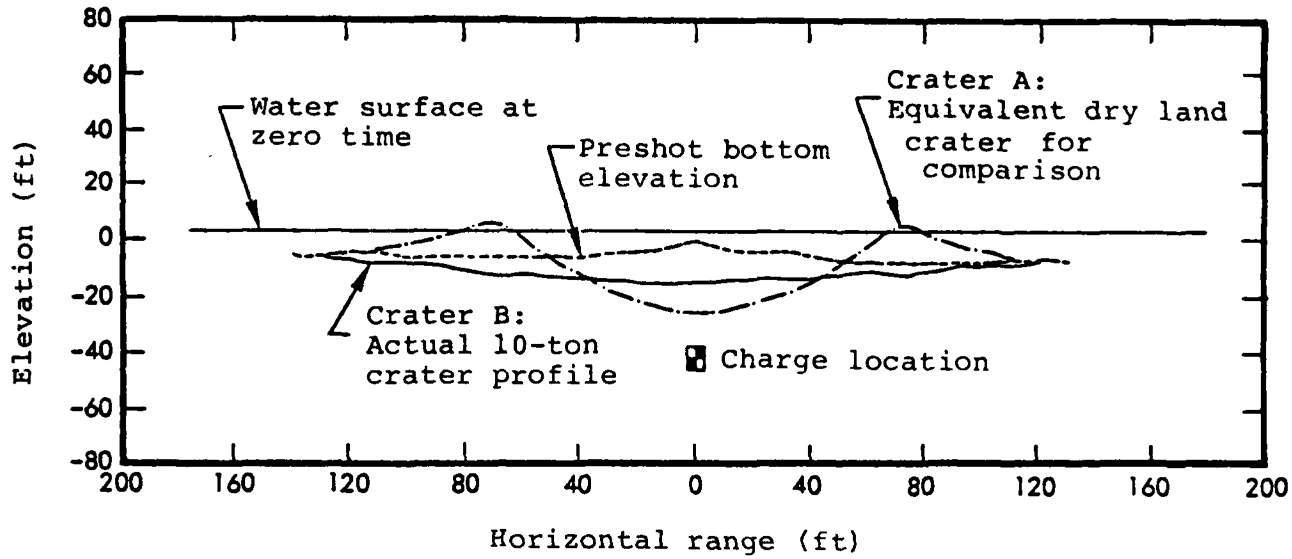


Figure 2. Comparison of Project Tugboat calibration shot crater profile with dry land crater profile. (Day]972).

$DOB = 11$ m (36 ft)

$R_a = 15.9$ m (52 ft)

$D_a = 7$ m (23 ft)

$H_{al} = 3.66$ m (12 ft)

A calibration series of shots including one 10-ton charge at the assumed optimum depth-of-burial of 11 m (36 ft) was planned because of lack of cratering experience with this material and with a water overburden.

2-5 CALIBRATION SERIES AND REDESIGN

The results of the calibration series (called Phase I) were completely unexpected and caused a radical change in the project design for Phase II. The crater resulting from the 10-ton detonation was flat and saucer-shaped, with no lips (see Curve B of Figure 2). The actual volume of the crater, measured with respect to the original ocean floor, was three to four times that expected on the basis of previous continental experience. The result was actually very fortuitous for the project. The wide, flat cross section was more desirable for this type of harbor project than the expected bowl-shaped ejecta crater, permitting a reduction from 20 to 12 charges of ten tons each in the final design. Figure 3 shows the final design configuration for the charges and the harbor outline. The charges were each ten tons of aluminized ammonium nitrate slurry emplaced with the charge center 12.8 m (42 ft) below mean low-low water (MLLW). The explosive was pumped into a metal cannister 1.6 m (5 ft) in diameter and 3.36 m (11 ft) in height with the hole backfilled with coral.

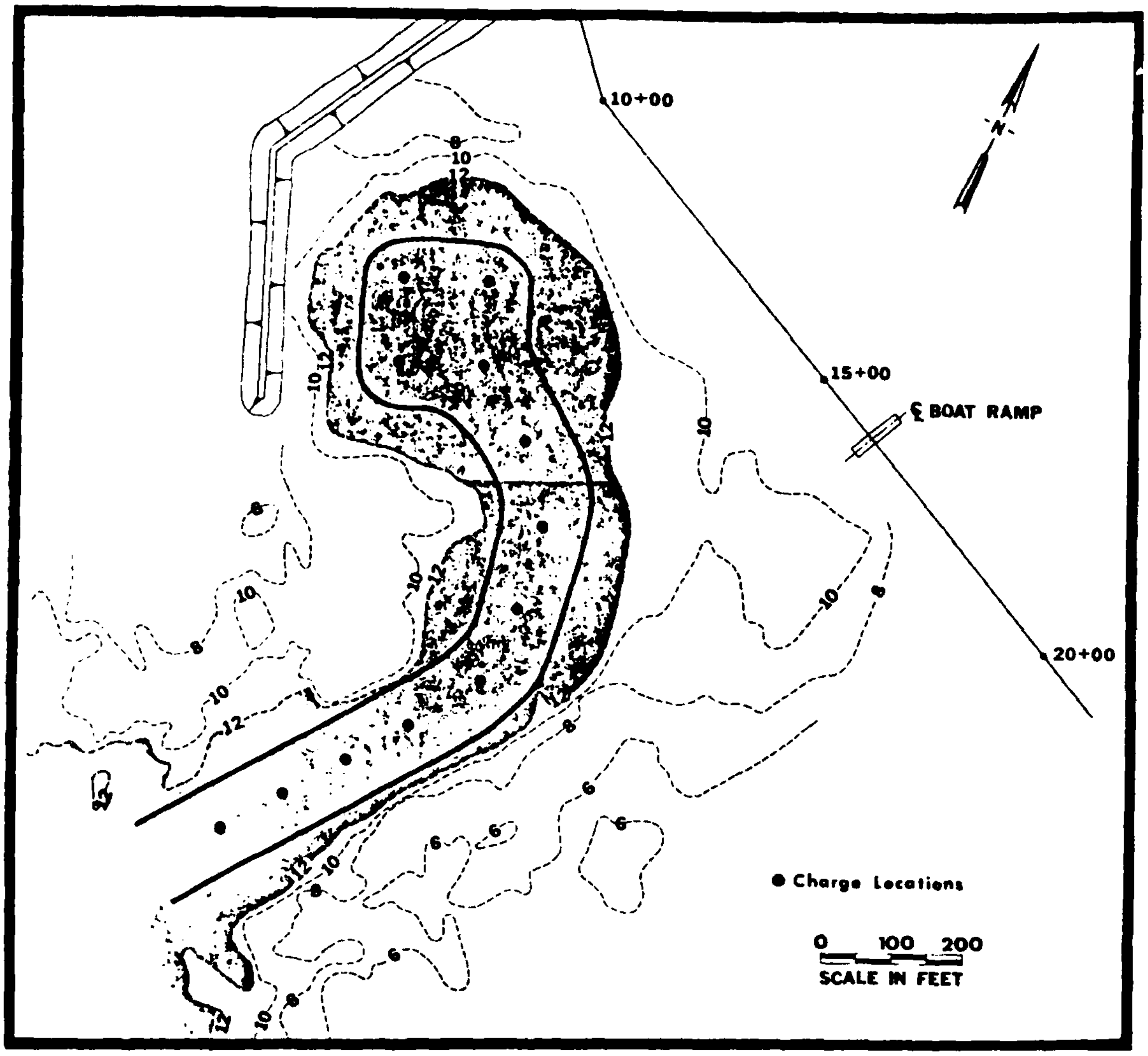


Figure 3. Plan view of 10-ton charge locations for Phase II (Day 1972)

2-6 TECHNICAL PROGRAMS

Many programs of a technical nature were carried out during the two-year period of Project Tugboat. The programs conducted which are applicable to this comparison study are briefly described in the following paragraphs.

Crater Measurements. Engineering surveys were conducted to determine the crater profiles and the resulting entrance channel and harbor basin dimensions.

Seismic Motion Measurements. A comprehensive seismic motion measurement program was undertaken during both Phase I and II. The objective of the Phase I program was to provide data as a function of yield, range, and depth of burst specific to the site that was subsequently used to determine the maximum safe yield for detonations in Phase II. During Phase II, measurements were made to verify safety predictions and to provide seismic motion and structural response data as a function of range and firing conditions.

Aerial Photography (Phase I and II) and Wave Measurements (Phase I).

A program of motion picture aerial photography of the Phase I and II detonations and a wave measurement program during the Phase I detonations only were conducted. The purpose of the photography was to provide documentation of the late-time crater formation process and to view the wave pattern produced by the detonations. The Phase I wave measurement program provided the first known wave data for underwater cratering detonations of significant yield.

Post-shot Engineering Properties Investigations.

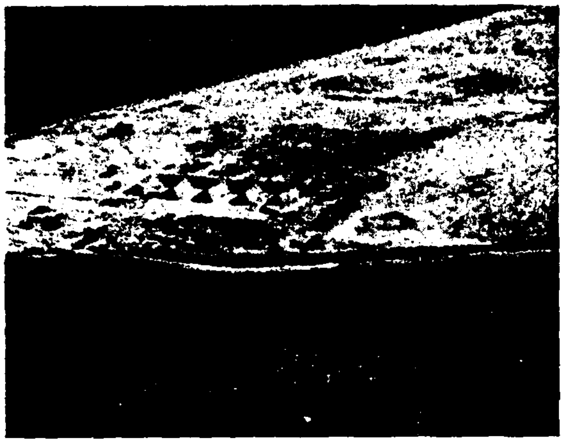
A program of drilling and sampling in the crater area was accomplished following the explosive excavation detonations in the berthing basin area and in the channel area to try to determine the extent of fracturing of the coral.

2-7 PROJECT EXECUTION

The four charges which were to form the berthing basin were detonated in May 1970 (DETONATION II-IJKL). An interesting shock wave interaction pattern was observed at the water surface for this detonation. Figure 4 shows pictures copied from high-speed movie frames showing the complex successive reinforcement and null pattern that formed a cross between the four charge locations. This phenomenon was investigated in detail and can be explained as being due to shock wave interaction in the near-surface water cavitated region over the charge locations. A sequence of frames from the high-speed aerial movies of this detonation will be examined in detail in Section 2-8. The film sequence from which the frames in Section 2-8 are extracted actually shows the late stages of the crater formation in real time.

2-8 CRATER FORMATION IN REAL-TIME

The aerial photography of the berthing basin detonation provided a unique opportunity to observe the real-time transformation of a "conventional, bowl-shaped ejecta or throwout crater" typical of continental cratering, into a flat, saucer-shaped crater similar to the



Charge layout just prior to Detonation II-IJKL.

Aerial photo taken just after detonation.

Detonation II-IJKL showing shock interaction and cavitation phenomena at water surface.

Changes in shock interaction and cavitation phenomena.

Figure 4. Shock wave interaction from detonation of four berthing basing charges (Day 1972).

nuclear-produced coral craters of the Pacific Proving Grounds. The camera was mounted on a nonvibrating mount in a helicopter, which hovered just out of ejecta range to the south of the detonation. This produced an oblique view of the crater with a changing scale due to the movement of the helicopter. Although steam and ejecta obscured the early stages of the cratering process, this cleared so that the crater was visible at approximately 32 seconds after the detonation. Because of the saturated nature of the coral and the water overburden, there was no dust cloud which normally obscures the cratered area for several minutes or longer after a continental cratering detonation. The entire area around the shot point and out some distance was essentially dewatered. Both the ejection process and wave action from the blast contributed to the dewatering. Ground-mounted cameras recorded a wave which moved out radially from the shot point. This action is described schematically in Figure 5.

Figure 6 is a photo, reproduced from the 72-frame/second color movie film, taken at approximately 34 seconds after the detonation. Although it is clearer and more easily seen in the actual movie, the outline of a water-filled crater is clearly visible as noted on the overlay of Figure 6. The diameter of the ejecta crater shown on the overlay is approximately 76.3 m (250 ft); this is very close to what would be predicted for this charge configuration if it were detonated in a continental situation using similar strength material, e.g., the saturated, wet-clay shale of Fort Peck. Also visible upon close examination of the movie is a portion of the lip of the ejecta crater. This is also detailed on the overlay to Figure 6.

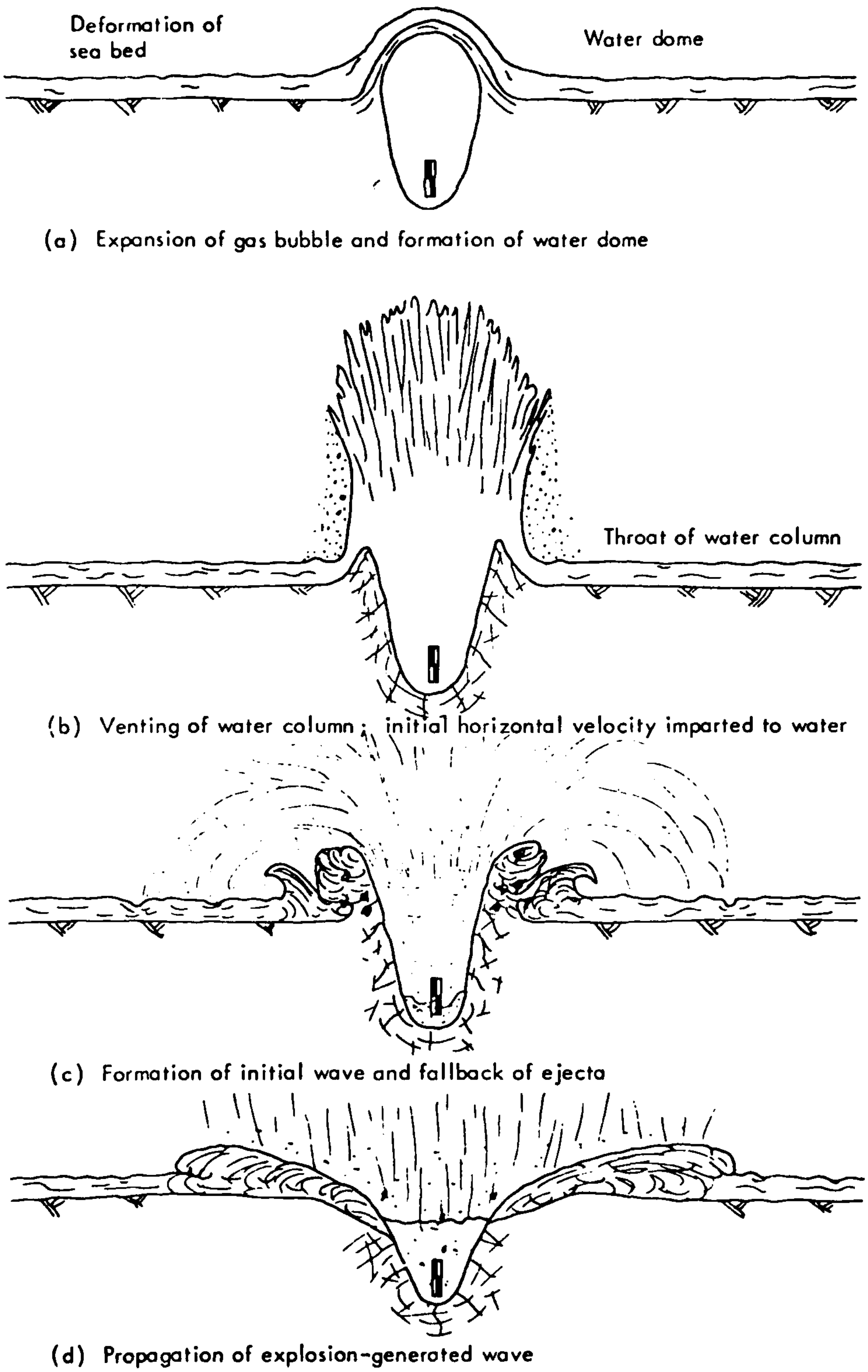
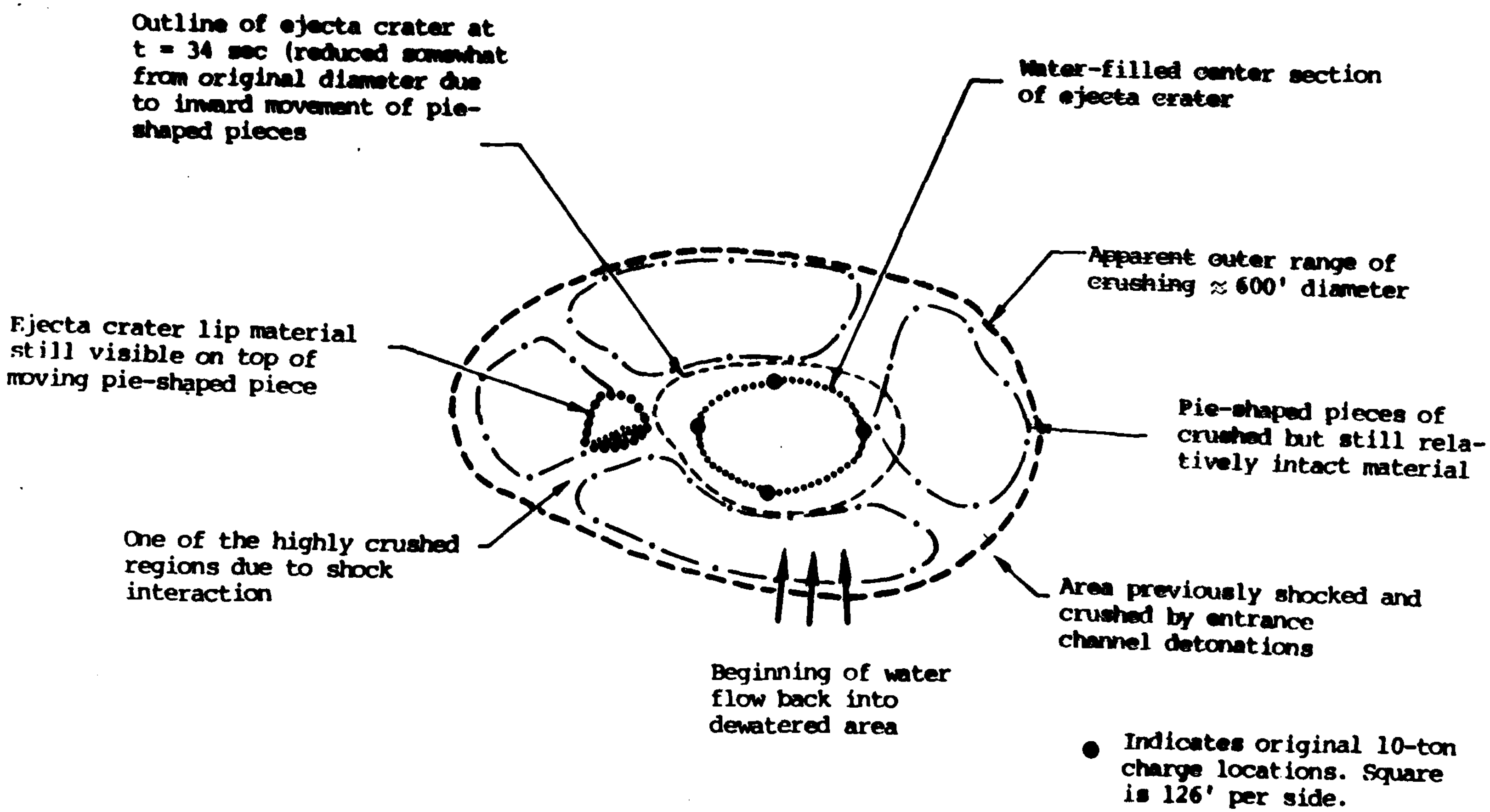
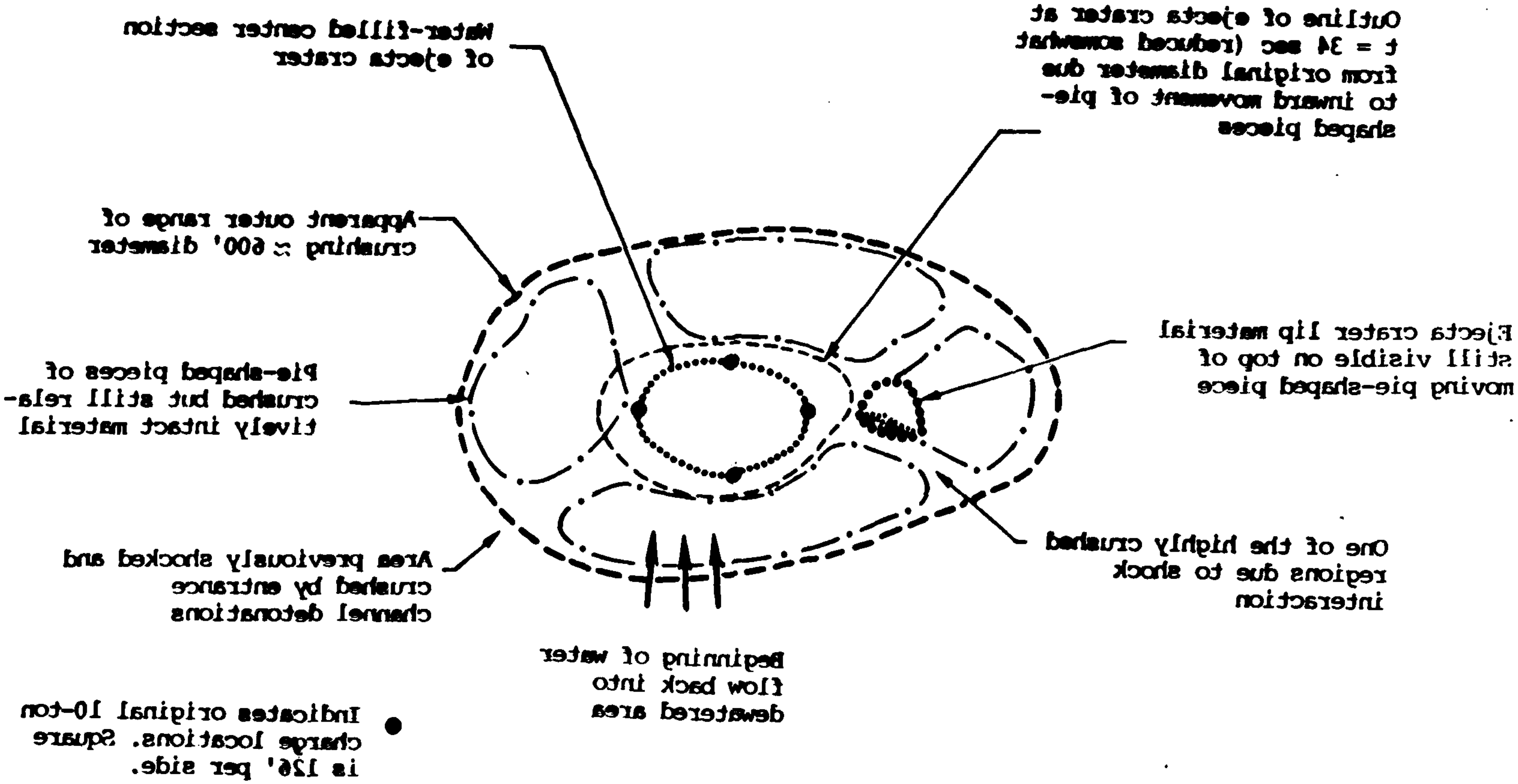


Figure 5. Generation of water wave by explosions beneath the sea floor.


Outline of ejecta crater at t = 34 sec (reduced somewhat from original diameter due to inward movement of pie-shaped pieces
Water-filled center section of ejecta crater
Apparent outer range of crushing ≈ 600' diameter
Ejecta crater lip material still visible on top of moving pie-shaped piece
Pie-shaped pieces of crushed but still relatively intact material
One of the highly crushed regions due to shock interaction
Area previously shocked and crushed by entrance channel detonations
Beginning of water flow back into dewatered area
● Indicates original 10-ton charge locations. Square is 126' per side.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One of the highly crushed regions due to shock interaction
Area previously shocked and crushed by entrance channel detonations
Beginning of water flow back into dewatered area
Indicates original 10-ton charge locations. Square is 126' per side.

Figure 6. Crater configuration approximately 34 sec after detonation.

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The approximate charge locations have also been shown on the overlay.

Two other details are immediately obvious in Figure 6, the "cross pattern" and the circular outline with a diameter of about that of the final crater, i.e., about 183 m (600 ft). The cross pattern corresponds to where the coral was very highly shocked and crushed by the interaction of the shock waves noted in Figure 4. The limit of the circular section is assumed to be the maximum range at which the motion resulting from the detonation was strong enough to crush or break the coral matrix. The fact that the center, water-filled crater area is slightly offset to the lower right of the photo, within the large outer circle, is expected since the coral in this direction was previously shocked by the detonation of the entrance channel charges.

In the next 10-15 seconds of real time, it is possible to observe in the movie the movement and slumping downward and inward of the pie-shaped pieces outlined in the overlay of Figure 6. This material, as noted in Section 2-2, had a total water-filled porosity of over 50 percent. With the cementation between the coral heads and pieces possibly broken by the explosion and the material partially crushed, settling and flowing under the force of gravity would be expected. This progressive action, as clearly seen in the movie, can be followed in Figures 7 through 9. These frames from the movie cover approximately five seconds of real time. During this period the material in the pie-shaped pieces flows inward and fills the original water-filled ejecta crater (see center of

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Figure 7. Crater configuration approximately 36 sec after detonation.

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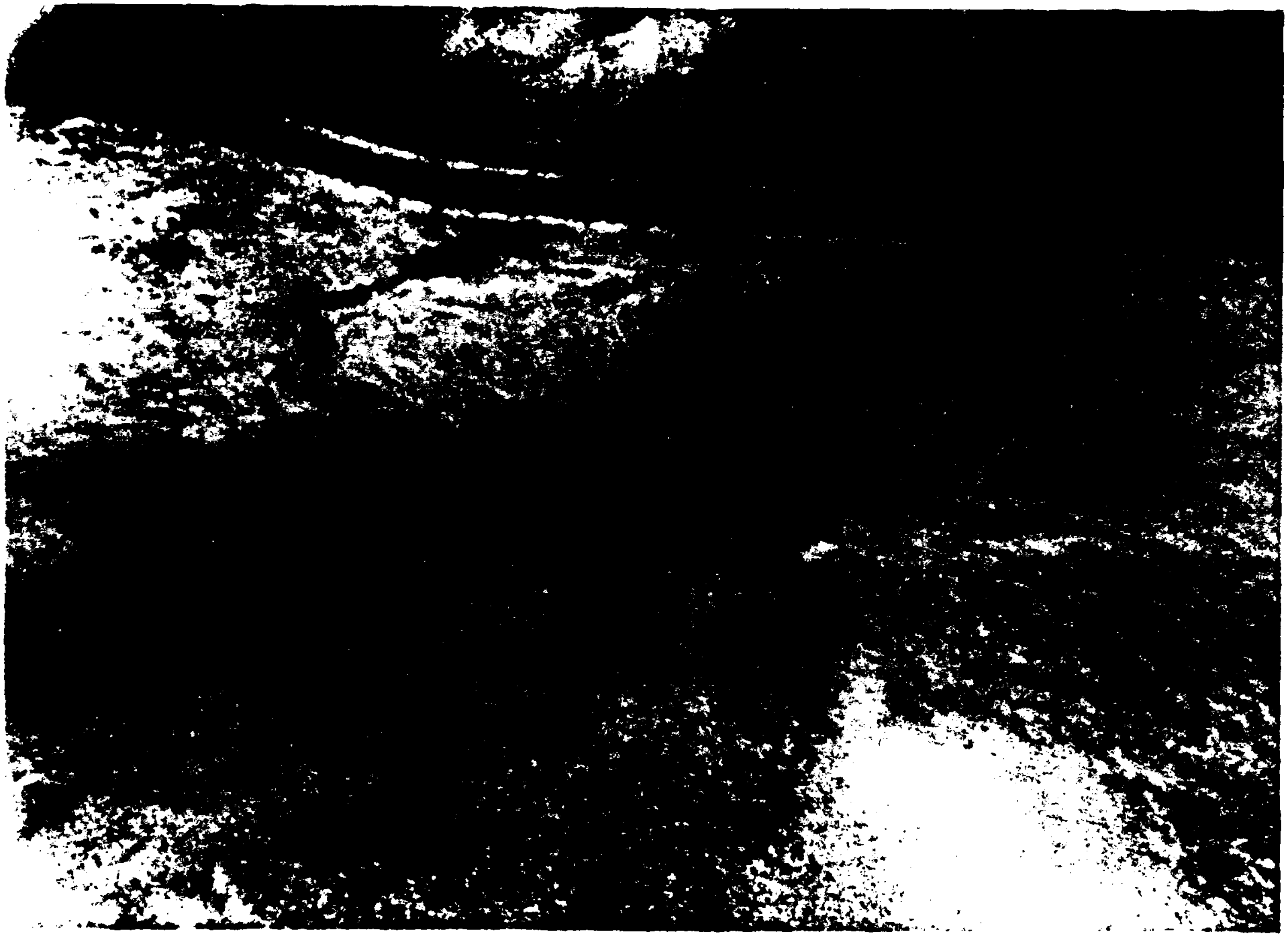

Figure 8. Crater configuration approximately 37.5 sec after detonation.

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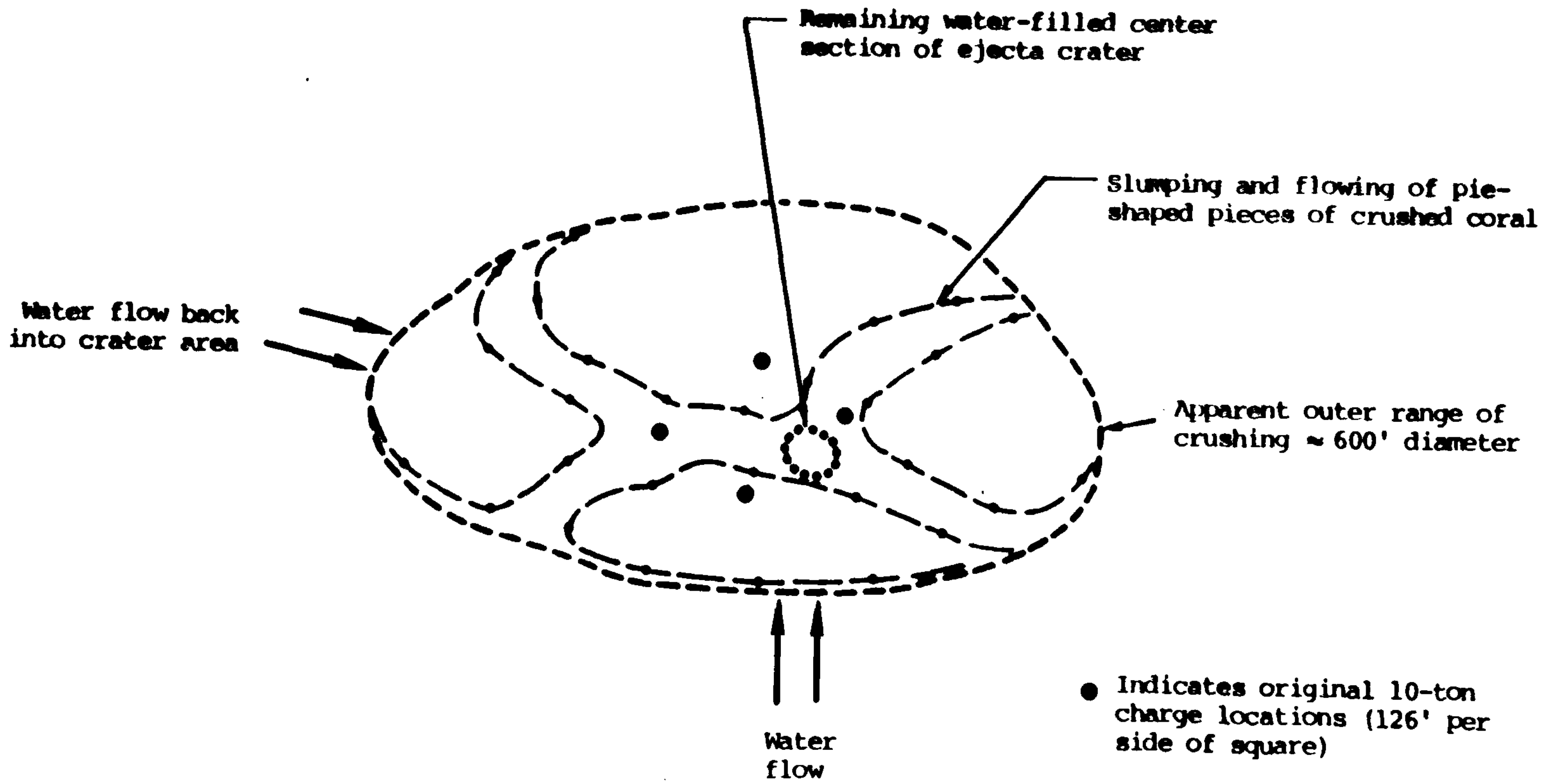
Remaining water-filled center section of ejecta crater
Slumping and flowing of pie-shaped pieces of crushed coral
Water flow back into crater area
Apparent outer range of crushing ≈ 600' diameter
Water flow
● Indicates original 10-ton charge locations (126' per side of square)

Figure 9. Crater configuration approximately 39 sec after detonation.

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Figure 6). The overlay on Figure 9 highlights the situation at T $\approx$ 39 sec, i.e., five seconds after that shown in Figure 6. Visibility of the details of the process is lost at about 45 seconds after the detonation due to water rushing back in to fill the cratered area. Complex surface motions and boiling action continued for some time in the crater area, presumably indicating the settling action or reconsolidation of the crushed coral under the influence of gravity and the consequent squeezing out of the water from the porous areas it had occupied prior to the detonation.

The rushing, washing action of the water as it flowed back into the cratered area, as noted above, would have carried with it any ejecta thrown beyond the crushed zone, and completed the process of smoothing out the crater or of converting it from the conventional, bowl-shaped, throw-out crater to the flat, saucer-shaped crater observed here at Project Tugboat and at the PPG nuclear craters.

2-9 CRATER CHARACTERISTICS

Several different types of investigation were carried out at the Tugboat site after the detonations to measure and record the post-shot conditions of the site materials. These investigations included acoustic sub-bottom profiling, probing, drilling, and underwater photography.

Isopack maps were made from the fathometer and tagline measurements taken immediately after the detonations. These maps show the thickness of the material displaced by the total cratering effort. The total volume of material excavated in Project Tugboat, as determined from the isopack maps, was determined to be 105,000 m^3 (Day 1972), which equates to a cratering efficiency of 875 m^3/ton (30,780 ft^3/ton) based on the 120 tons of explosive used. Based on the original design (Day 1972), which used clay shale experience (Johnson 1971), a volume of approximately 268 m^3/ton (9450 ft^3/ton) was expected, indicating an enhancement or increased effectiveness by a factor of 3.25. This may be attributable to the crushing and compaction effect in coral versus the "conventional throw-out mechanism" experienced in continental cratering. The fathometer and tagline surveys were repeated seven months after the detonation. These surveys showed a general lowering of the bottom by an average of two feet. Although some of this could be attributed to washing and scouring action, long-term settling effects were also noted during an acoustic survey several days after the detonation. An anomalous noise was noted in the center of the crater. Hydrophones, which were then placed on the sea floor, detected sharp clicking and snapping sounds, evidencing active settlement of the crushed coral. If even one-half of the additional depth of two feet noted after seven months was due to long-term settling effects, the volume attributed directly to the cratering would increase to 1100 m^3/ton (38,780 ft^3/ton) and the enhancement or increased effectiveness would increase to approximately four times the expected continental results.

2-10 ACOUSTIC PROFILING

Acoustic (seismic) sub-bottom profiling was carried out both before and after each of the detonations. Two separate systems were used: an 8.5 kHz (high-frequency) high-energy sonar and a 250 Hz (low-frequency) 16-joule pulser system. The pulser records were the more useful. In the December 1969 preshot survey, a strong, reflecting horizon was detected approximately 30.5 m (100 ft) beneath the ocean surface. This was interpreted as being the top of the basalt underlying the coral. After the 10-ton calibration shot was fired, two reflection survey lines were run across the crater. The same strong reflection lines at about 30.5 m (100 ft) depth were present but they were noted only at the ends of the lines and were missing over the crater itself (see Figure 10). The assumed reason for the lack of the basalt reflection in the crater area was that the acoustic signal was attenuated in the discontinuous fractured coral in and adjacent to the crater. The presence or absence of the basalt reflection thus offers a clue to the boundary of the rupture zone.

Results from the two survey lines also showed three separate, strong, reflecting horizons defining the crater itself. The deepest of these reflections, at approximately 13.7 m (45 ft), was bowl-shaped with a small depression in the center, and might indicate the boundary of the true throw-out crater. The upper reflections, which slope gently toward the crater center, evidently represent sedimentary beds of materials which were deposited following the blast (fallback material which liquified and flowed back into the ejecta crater, and washback.) Although it is conceivable that one or more of these reflecting horizons could be due to multiple reflections, the clarity and longitudinal extent mitigates against this possibility. Figure 10 shows the results of the acoustic survey discussed above in schematic form.

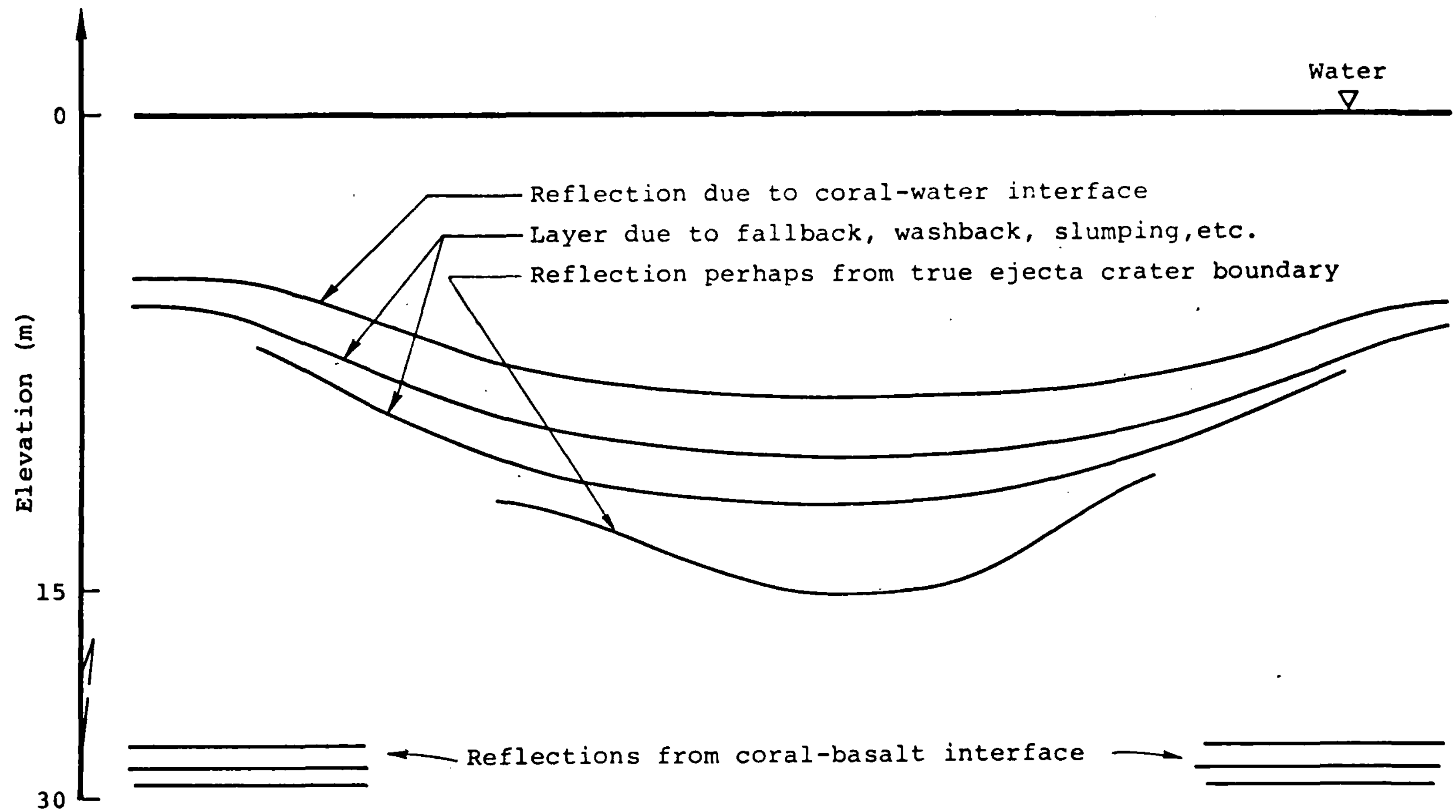

Figure 10. Schematic of seismic survey results across crater from 10-ton test charge.

In the May 1970 surveys following the main project detonations, the basalt reflection showed up consistently at the ends of the traverse lines, but failed to show up in the central area of the craters. The sections of the line profiles where the basalt reflections were missing, correlated well with the outer limits of the flat, saucer-shaped portions of the resulting craters.

2-11 PROBING

Hand probing of the crater from the 10-ton calibration shot was conducted with a 1/2-inch pipe immediately after the detonation. It was possible to probe to 12.2 m (40 ft) below MLLW without difficulty. (Charge center had been at 12.5 m [41 ft] below MLLW.) No boulders or coral fragments were hit. A second probing was tried approximately three weeks later. The maximum depth which could be probed at this time was 10.4 m (34 ft), probably due to an increase in density caused by settlement and consolidation.

2-12 DRILLING

The planned drilling program following the detonation was limited by both financial and technical constraints. The preshot drilling had shown that the material was extremely difficult to core. Even in its undisturbed state, all drill holes had to be cased to their full depth. The probing after the detonation indicated a soft layer of mud several feet thick over the area, which would have made conditions difficult for firmly placing a drilling platform. The acoustic profiling had indicated that the coral had probably been shattered both in the immediate crater area and for some distance outward. Therefore, coring was rejected since it was anticipated that core recovery would be even poorer in the fallback, washback, and blast-fractured materials than it had been in the undisturbed coral reef. To be successful in recovering materials in an undisturbed state would have required a large-diameter tool (> .15 m [6 in]) and conceivably could not have been accomplished short of a more sophisticated technique, such as freezing.

In an attempt to obtain some data, it was decided to try a drive method of wash boring, with the hope that the penetration resistance might give some indication of the quality of the foundation with depth, and that the wash borings would provide an indication of increased density with depth. Although the penetration resistance did give some indication of whether or not the material had been crushed, and aided in the lateral determination of the range of crushing, it was of no help in depth determination. It was impossible to tell from the split-spoon drive samples whether the coral materials had been shattered by the blasts and whether they had been disrupted or reoriented. Because of the large amount of fines lost in the washing process, it was also impossible to verify any degree of increased densification.

SECTION 3

PACIFIC PROVING GROUNDS CRATERS

3-1 BACKGROUND

The nuclear tests conducted by the United States in the Eniwetok and Bikini Atolls during the 1950's were primarily device tests. Nevertheless, the craters produced by these detonations have assumed critical importance in nuclear weapons effects planning, since they are basically the only nuclear surface burst craters available for evaluation. Two major problems have resulted from attempting to use these craters for the effects data base. First, since the cratering effect was not one of the objectives of the tests, little attention was paid to geology, ground motion, air and ground pressures, etc., all of which are critical to effects prediction and theoretical modeling. Second, the detonations left wide, flat, saucer-shaped craters which have considerably greater volumes than those expected and calculated using computer codes and calculational techniques based on more conventional, dry-land cratering experience.

In addition to the general problems cited above, analyzing these craters from the Pacific Proving Grounds (PPG) is confused by numerous other factors. Many of the crater measurements were not made until years after the detonations, by which time washing, wave action, and erosion had probably affected the craters significantly.

The configuration of the tests varied considerably. Some devices were fired in large, water-filled tanks, which would tend to couple more energy into the ground and affect the size of the crater expected. Some shots were fired in towers, while others were located on barges. Two shots may, therefore, have been equidistant above the coral material being cratered, but the results would be expected to be quite different due to the different density of the intervening material, air or water. In several cases a test was conducted sufficiently close to where a previous device had been detonated that the craters overlapped, or at least the second crater was formed in material previously shocked by high pressures. If the primary mechanisms of formation for these craters are crushing, compaction, and consolidation, as the investigation implies, the crater from the second event would be expected to be smaller than if it had been detonated over unperturbed coral material.

Considering all of the above factors, there is an amazing consistency in the cratering results from the high-yield shots at PPG, as discussed in Section 3-3. The cross sections are quite similar - flat and saucer-shaped, with a general lack of lip and upthrust around the craters; and the "cratering efficiency" in terms of volume/ton is relatively constant, with several explainable anomalies (Ristvet 1978).

3-2 GEOLOGY

Various drilling and subsurface investigations of the coral atolls throughout the Pacific have been conducted (Ristvet 1978). The most consistent factor noted throughout the reports on these investigations is the variation of the coral material both vertically and horizontally, even between drill holes with only a few meters separation. As discussed in Section 2, coral is remarkably different from other rocks. It is formed by the combination of many lime-secreting invertebrate marine animals (anthozoans or polyps) and millipore algae plants (thallophytes). They secrete an elaborate, rigid limestone latticework, which is highly porous, brittle, and easily broken when in the fresh state. As the network expands upward and outward, older forms die and gradually the dead base is buried by the growth of other animals and by the abundant rock debris that waves break from the living parts. The shells that remain as the polyps die become filled with a saturated solution of calcium carbonate or sand. Water and time causes some of the material to harden while dissolving the softer parts, thus leaving many holes and crevices.

Since the conjecture of this report is that the coral is crushed and compacted or densified to a range and depth corresponding to where the pressure (impulse) exceeds the strength of the coral, the near-surface region is of primary importance. A generalized model for the near-surface geology (Henny, Mercer, and Zbur 1974) is illustrated in Figure 11. Figures 12 shows drilling data from boreholes on Eniwetok Atoll. The upper region is comprised of mostly soft and/or cavernous rock with a few thin, hard layers. The average hard/soft ratio for the material from 0 to 335 m (1100 ft) below MLLW is 0.13 (Ristvet 1978). The number of large voids and total or reef porosity is not known but circulation loss in coral drilling operations and poor core recovery is common, requiring consequent casing of the holes.

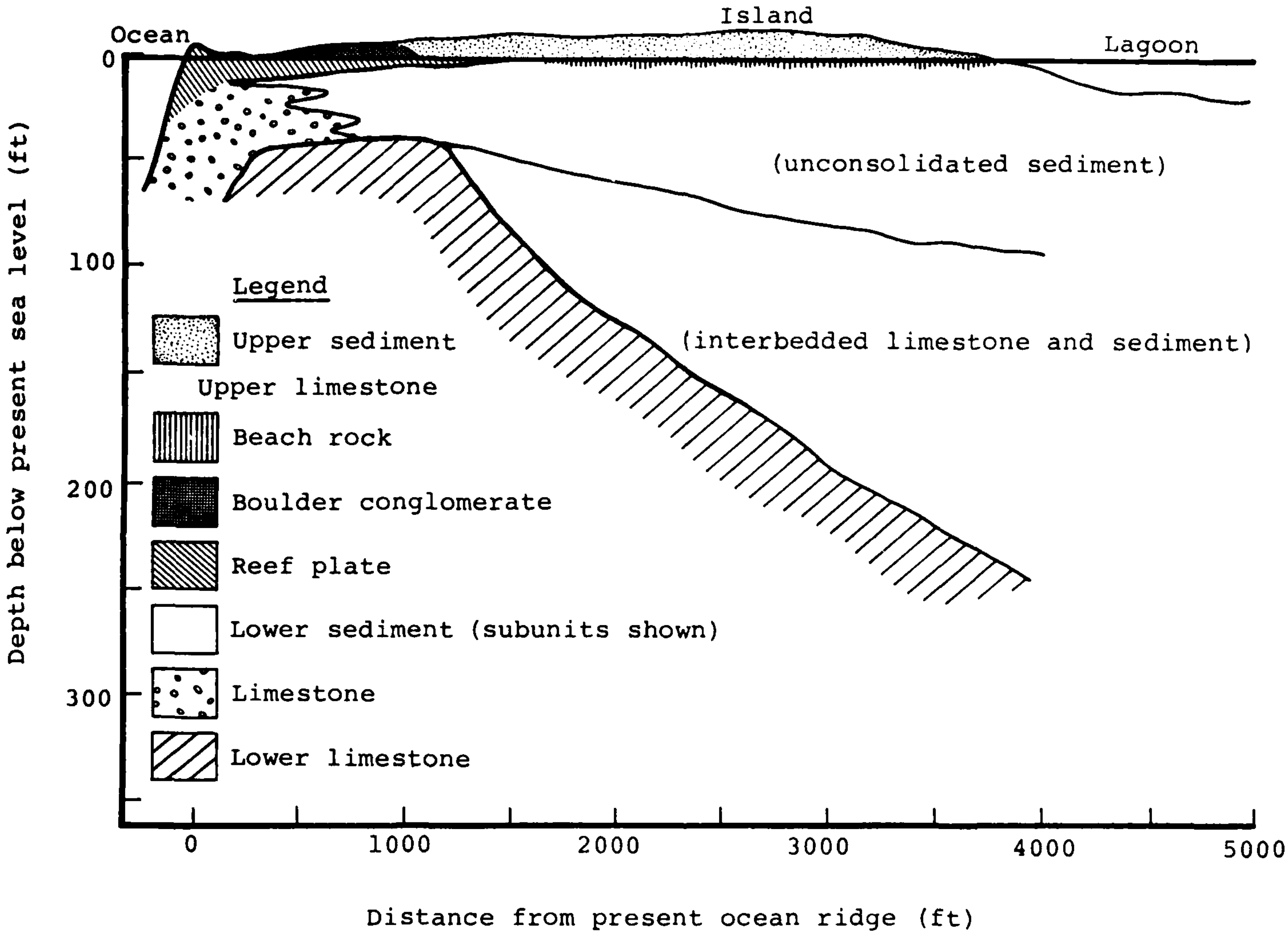

Figure 11. Near-surface geologic model for Eniwetok Atoll. (Henny 1974)

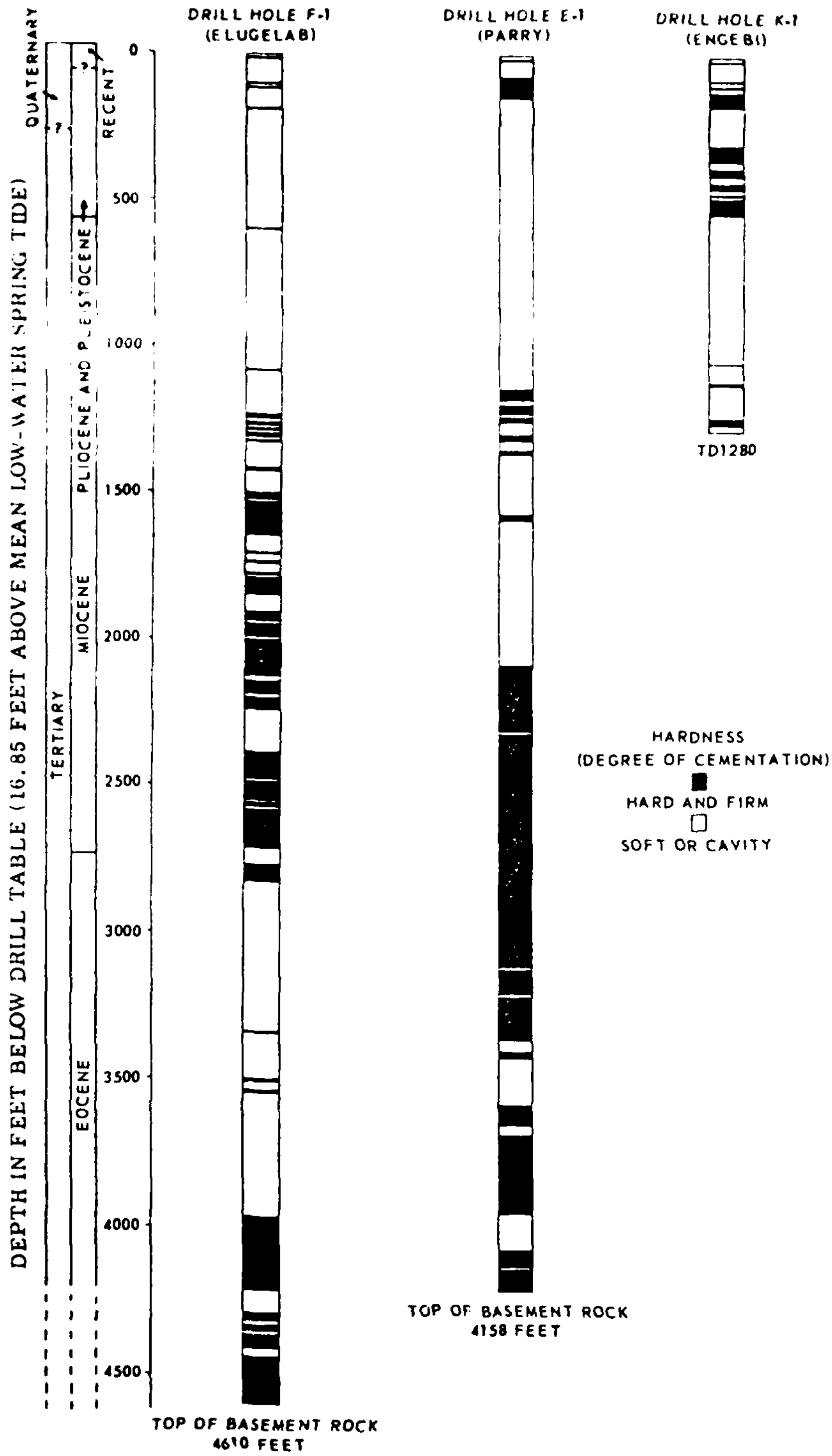

Figure 12. Drilling data from deep boreholes on Eniwetok Atoll. (Source: USGS Prof. paper 260-Y, 1960)

3-3 CRATER CONFIGURATIONS

The cross sections of the PPG craters in coral caused by high-yield devices are flat and saucer-shaped when compared to the bowl-shaped craters more commonly found in continental cratering. Some generalized profiles of PPG events are shown in Figure 13. The yield and crater dimensions for these events are listed in Table 1.

The KOA and SEMINOLE events should be eliminated from an evaluation of crater efficiency since they were fired in water-filled tanks, effectively coupling considerably more energy into the ground than their nominal yield would indicate. Considering the remaining eight events and ignoring differences due to height-of-burst gives an average cratering efficiency factor of approximately 3.4 m^3/ton (120 ft^3/ton), with a standard deviation of $\pm$ 1.3 m^3/ton (46 ft^3/ton). There are anomalies associated with several of the other events which could also warrant their exclusion from the list of calculating the average. LACROSSE and CACTUS were relatively low-yield events and it is possible that insufficient energy was coupled either directly or by air blast overpressure to crush the coral matrix much beyond the radius of the throw-out crater range. Also they may have been on the reef rock which was a relatively stronger material. ZUNI, although a large event, would be expected to produce a smaller crater if crushing and compaction are the primary cratering mechanisms, since it was detonated on the edge of the KOON crater. The area had already, therefore, been subjected to high pressures and had consequently been crushed and consolidated to some degree. If one eliminates these events, the average cratering efficiency for the remaining five events becomes 4 m^3/ton (142 ft^3/ton), $\pm$ 1.2 m^3/ton.

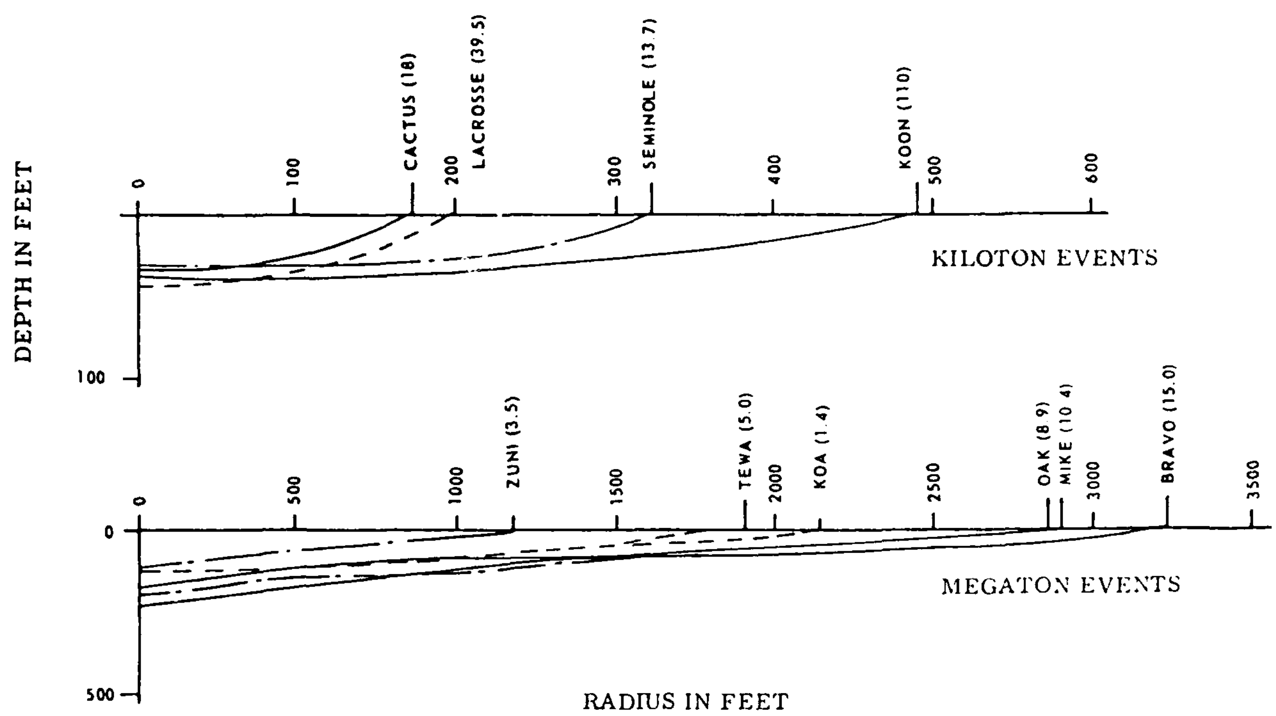

Figure 13. Generalized Pacific Proving Grounds crater profiles (Ristvet 1978).

Table 1. Crater dimensions from test events at Eniwetok and Bikini Atolls (Ristvet 1978).

Operation	Event	Yield (kt)	HOB[1] (ft)	Radius[2] (ft)	Depth GZ[3] (ft)	Max. Depth[4] (ft)	Volume $\times 10^{+6}$ (ft^3)	Efficiency (ft^3/ton)
IVY	MIKE	10,400	10.0	2910	136	187	1236	118
CASTLE	BRAVO	15,000	7.0	3255	250	250	2025	135
	KOON	150	9.6	495	40	40	14	94
REDWING	LACROSSE	39.5	8.0	200	54	56	3	78
	ZUNI	3,380	10.0	1165	93	113	202	60
	SEMINOLE	13.7	7.0	324	32	32	7	510
	TEWA	4,600	10.0	1915	133	133	742	161
HARDTACK-1	CACTUS	18	3.0	173	34	37	2	110
	KOA	1,300	2.7	2160	170	170	745	573
	OAK	8,900	5.8	2870	197	204	1825	205

[1]Distance between "center of energy" of device and foundation surface beneath the surface.

[2]Measured at the zero difference contour.

[3]Difference between foundation elevation and the point directly beneath GZ within the crater.

[4]Difference between the fundation elevation and the deepest point in the crater.

SECTION 4

ANALYSIS AND COMPARISON

The fact that both an optimum depth, high-explosive cratering experiment in coral (Project Tugboat) and the Pacific Proving Grounds (PPG) nuclear detonations over coral produced similarly shaped craters and, in the first case, of larger size than expected, is of considerable significance in understanding and predicting the cratering efficiency for nuclear surface bursts. An analysis of the two cases indicates crushing and compaction may be the dominant effect for producing the final crater volumes. Based on a known relationship between high-explosive cratering in coral and a similar continental material, a prediction is suggested for continental nuclear, surface cratering efficiency using the PPG results.

4-1 ASSUMED NUCLEAR CRATERING PROCESS

The following schematics show the assumed PPG cratering process. The scenario is based on the Tugboat high-speed movies of the high-explosive cratering process in coral, the Tugboat seismic programs, and PPG seismic surveys.

Figure 14a shows a generalized PPG predetonation view. Figure 14b schematically indicates the energy coupling from the device, both direct and air blast-induced. Figure 14c depicts the ejecta cratering process, showing the dewatering that takes place after a blast.

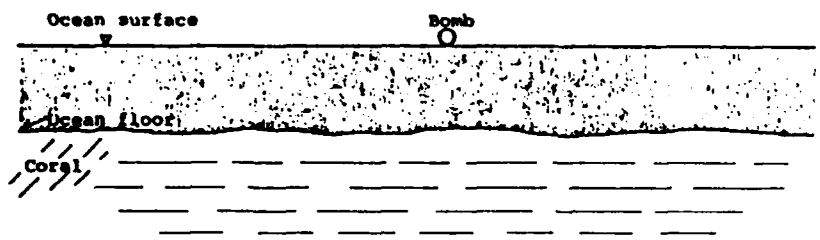

Figure 14a. Generalized PPG predetonation condition.

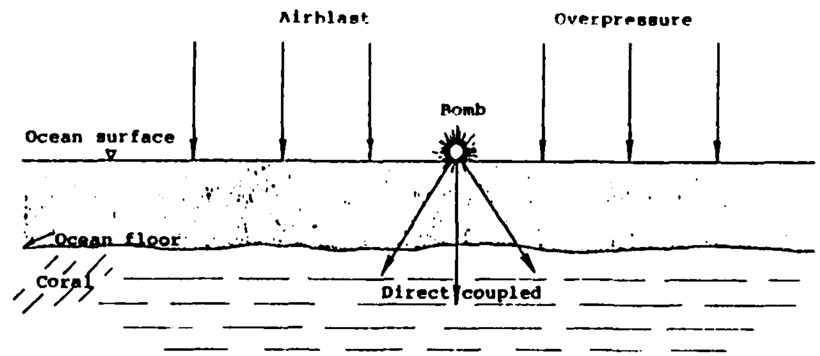

Figure 14b. Energy coupling just after time of detonation.

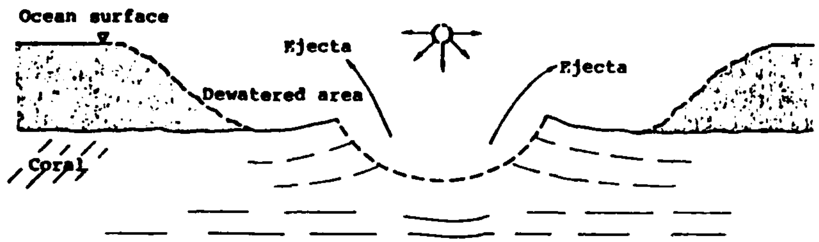

Figure 14c. Ejecta and dewatering processes.

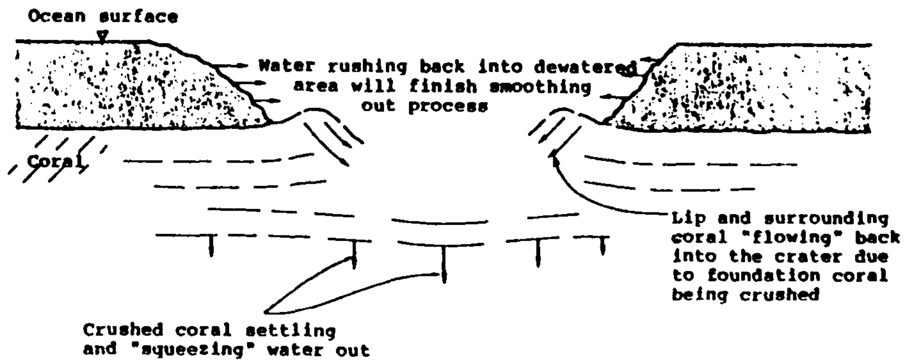

Figure 14d. Crater reshaping due to media and site-specific characteristics.

Figure 14. Schematic of assumed Pacific Proving Grounds crater formation process.

Figure 14d shows numerous phenomena taking place as equilibrium is being restored; the lip and crushed coral above the bottom elevation of the open ejecta crater begin to flow and level out, water is rushing back into the dewatered area carrying ejecta back into the crater, and the undisturbed but crushed coral is gradually settling under the influence of gravity.

If it is assumed, as was observed on Tugboat, that essentially all of the material ejected in the throw-out crater process ends up back in the final crater, it must also be assumed that the entire observed crater volume is due to the settling and compaction (reconsolidation) of the coral material crushed or liquefied by the shock wave from the detaonation. This conclusion is depicted schematically in Figure 15. Further credence is given to this conclusion by the seismic results of Project Tugboat (Day 1972). These seismic results are also shown graphically and explained in Figure 15.

The existence of peak pressures of sufficient magnitude to crush the coral matrix at large distances into the ground under a nuclear detonation is predicted by code calculations as shown in Figure 16. This figure illustrates the results of the S-Cubed SOURCE 3/5 calculation (Rimer 1980) of a 1-MT nuclear surface burst over wet tuff. The solid lines indicate the contours of material processed by pressures equal to or exceeding the indicated values. The dashed line shows the calculated throw-out crater for this event, which represents an efficiency of $\sim$ 30 ft^3/ton. The dashed-dot lines indicate a possible "compaction" crater caused primarily by the disruption of the coral matrix by the shockwave and its subsequent reconsolidation.

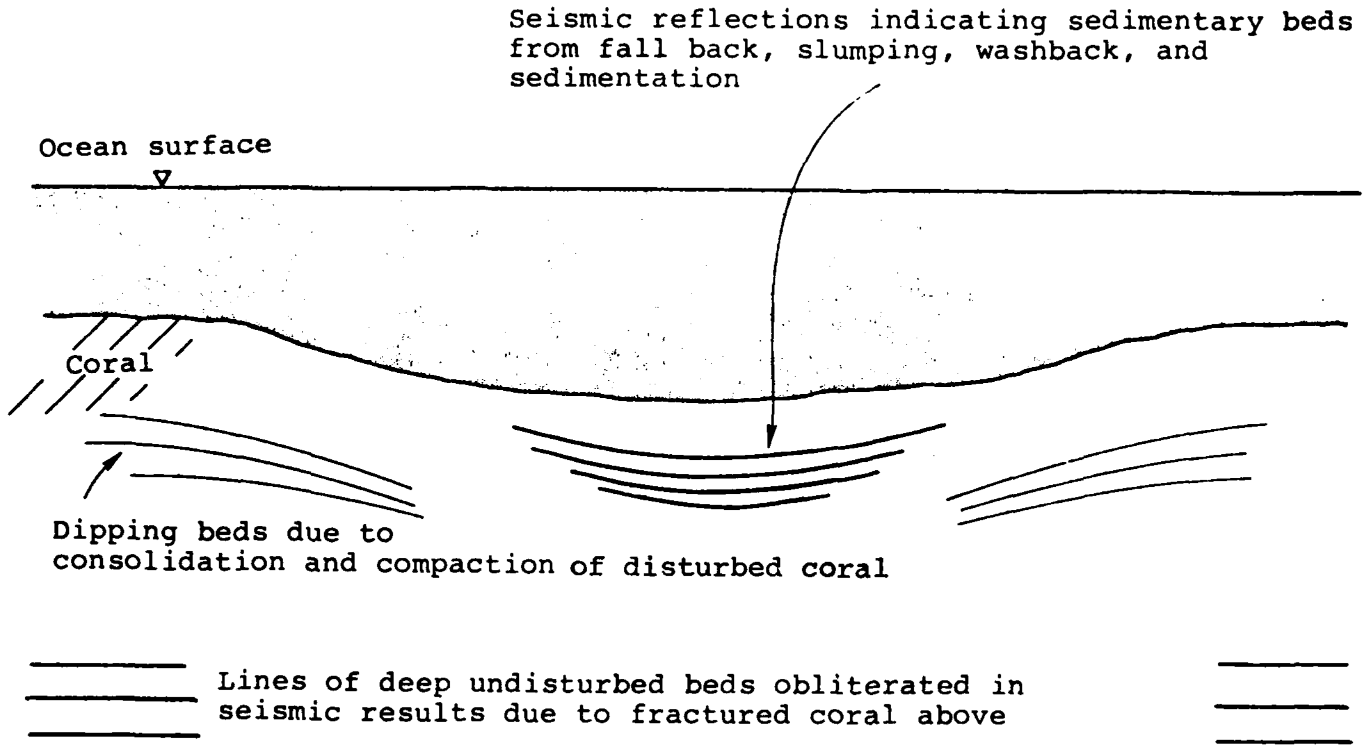

Figure 15. Schematic of assumed final crater configuration for Pacific Proving Grounds craters.

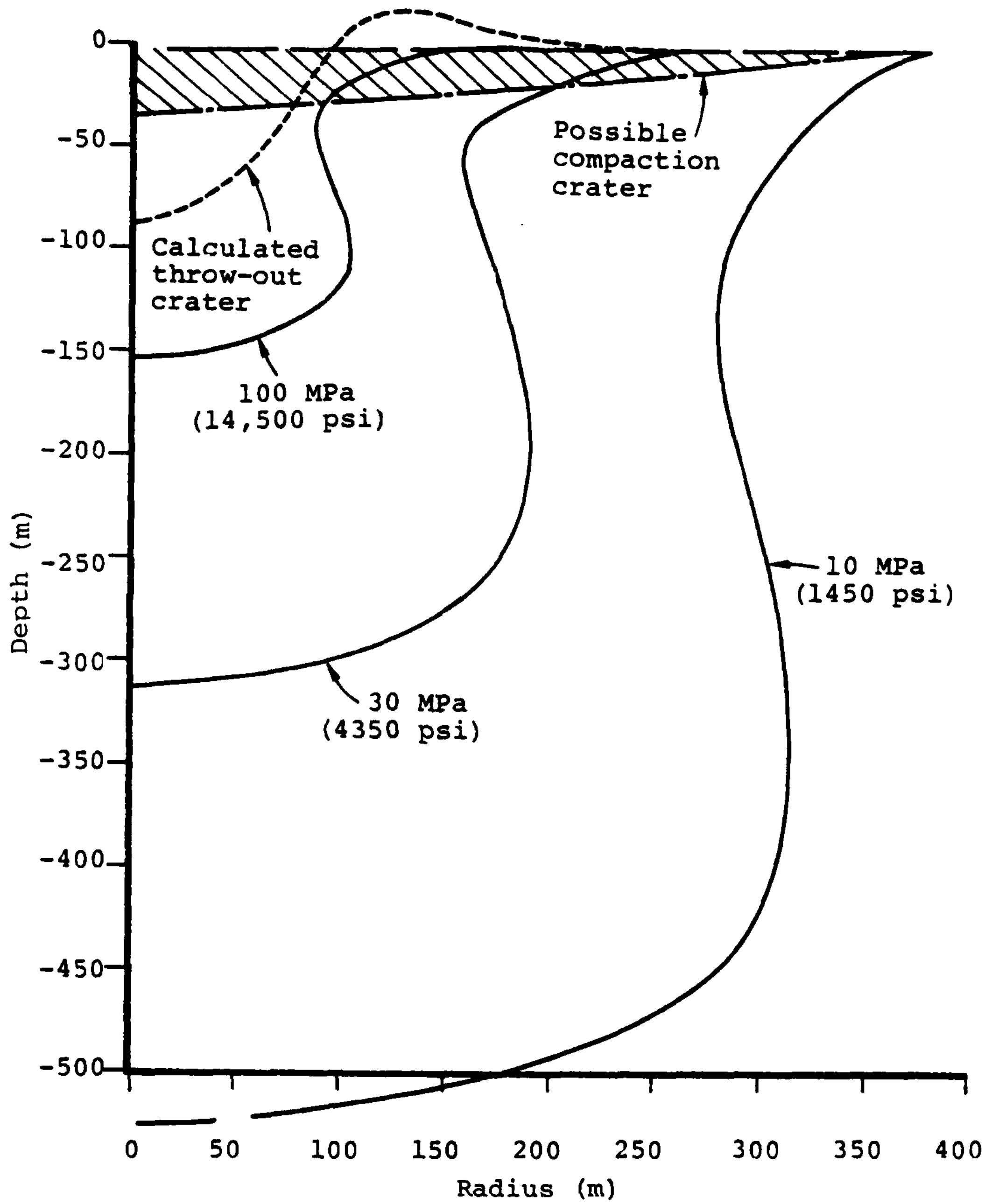

Figure 16. Prediction from SOURCE 3/5 code calculation for peak pressures beneath a nuclear surface-burst and approximate Pacific Proving Grounds crater profile for similar size device.

This compaction crater is based on a purely hypothetical model for compacting. The relative compaction, δ, following passage of a shock of strength P is assumed to be given by:

$$\delta = 0 \qquad P_{max} \leq 10 \text{ MPa (1450 psi)}$$

$$\delta = 0.1 \frac{\ell n\ (P/10)}{\ell n\ (.69)}, \qquad 10 \text{ MPa (1450 psi)} \leq P_{max} \leq 1000 \text{ MPa (145,000 psi)}$$

$$\delta = 0.1 \qquad P_{max} \geq 1000 \text{ MPa (145,000 psi)}$$

That is, an amount of material having vertical extent Δy, processed by a shock of strength P, then is assumed to be compacted on some time scale to a vertical extent of $(1-\delta)\Delta y$. The degree of consolidation of the coral is relatively independent of the peak stress once the matrix is broken, i.e., all or nothing.

From the above analysis, it is concluded that although the conventional throw-out crater process is present, it contributes little to the ultimate crater shape and volume. The final crater volume is three to four times that expected, based on a throw-out crater phase. The crushed coral and water mixture "liquefies" and, under the influence of gravity, flows to fill the throw-out crater. After the coral settles, a resulting flat, saucer-shaped crater is observed. The crater volume is due to the reduction of porosity both on the microscopic scale (solid, intact cores of coral have porosities of 40-50 percent) and, perhaps more importantly, on the macroscopic scale (the large voids and caverns within the coral reef.) The high permeability of the coral allows the water to flow out as the compaction proceeds.

4-2 COMPARISON OF HIGH-EXPLOSIVE AND NUCLEAR CRATERING PROCESSES

There are major differences, e.g., pressure, temperature, duration, etc., between the effects of a high-explosive and nuclear cratering detonation, even when all possible measures have been taken to attain simulation. However, in comparing cratering efficiency, there are two unique factors which suggest a direct extrapolation from Project Tugboat to the PPG craters. There is a direct comparison available between high-explosive cratering in coral (Project Tugboat) and high-explosive cratering in a dry-land medium of wet, soft rock (Fort Peck) (LaFrenz 1970). This wet, soft rock had approximately the same characteristics as the coral except for the macroscopic porosity, the high permeability, and the water overburden. Cratering experience with the rock was used as the original design basis for the coral cratering. The second factor permitting comparison relates to the apparent mechanism by which craters form in a coral medium.

The crushing of the coral by a shock wave and the subsequent settling should occur regardless of whether the shock wave traveled through the ground from the buried charge or was air blast induced. Once the coral is crushed, the remainder of the cratering sequence (shown photographically in Figures 6 through 9, and schematically in Figure 14) should proceed the same regardless of the source type and location.

The comparison cycle shown in Figure 17, which is based on the above factors, graphically depicts the rationale justifying the prediction of paragraph 4-3 for

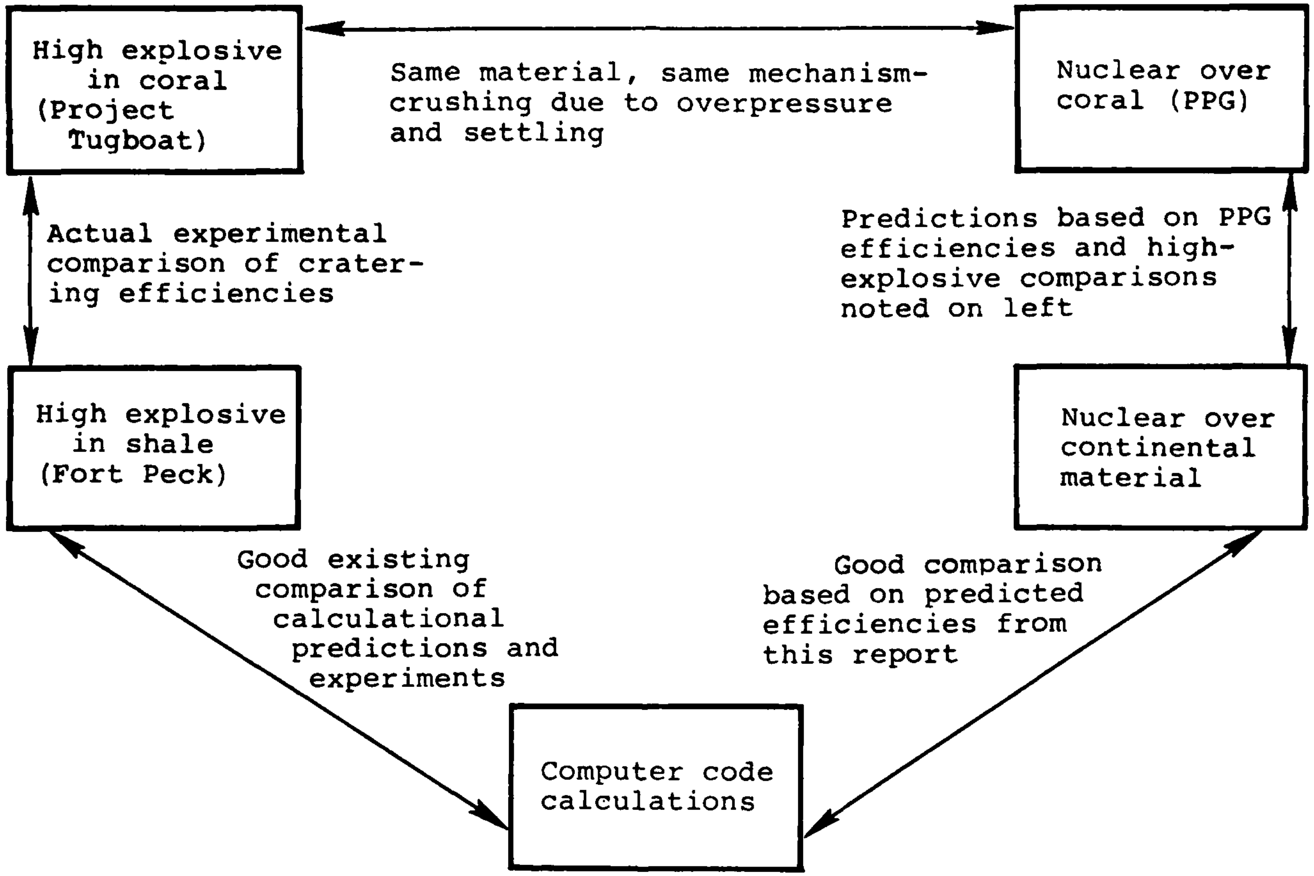

Figure 17. Comparison cycle for high-explosive and nuclear cratering effects.

continental cratering efficiency for nuclear surface bursts. The existence of a throw-out crater for high-explosive detonations, both from a surface-burst continental condition and in the initial stages of the optimum depth detonation in coral, lends further credence to assuming the same comparison for the nuclear case.

4-3 PREDICTIONS FOR NUCLEAR CRATERING EFFICIENCY

There are many logical explanations for the wide variation in the cratering efficiency for the various PPG events (Ristvet et al., 1978; Brode 1979). The heights-of- burst varied, some devices were suspended in water tanks, massive concrete test stands were placed adjacent to some devices, some devices were detonated in areas already highly shocked by previous shots, and the amount of water overburden varied from zero to several hundred feet. All of these factors plus the variability of the coral with depth and location require a heavy judgment factor in determining an average cratering efficiency factor. As discussed in paragraph 3-3, the PPG cratering efficiency ranges from about 3.4 to 4 m^3/ton (120 to 140 ft^3/ ton). If an average value of 3.7 m^3/ton (130 ft^3/ton) is used for PPG craters with the conversion ratio of 4 (paragraph 2-9) for coral to wet rock from high-explosive experience, an equivalent cratering efficiency for nuclear surface bursts over land would be

$$\frac{3.7\ \text{m}^3/\text{ton}\ (130\ \text{ft}^3/\text{ton})\ \text{at PPG}}{4\ (\text{conversion ratio})} = 0.9\ \text{m}^3/\text{ton}\ (32\ \text{ft}^3/\text{ton}$$

over land (wet, soft rock). This is shown diagrammatically in Figure 18, following the logic of paragraph 4-2.

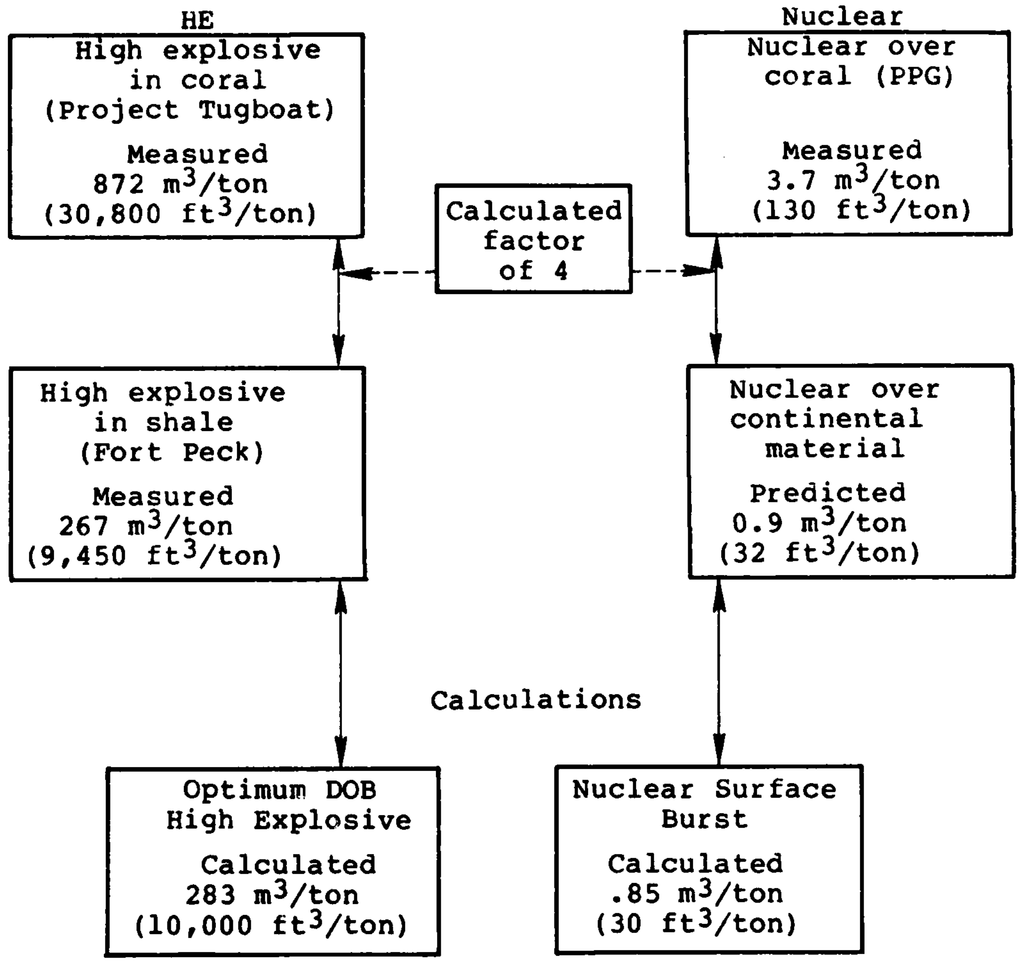

Figure 18. Predictions for nuclear surface burst cratering efficiency in a continental mode.

SECTION 5

SUMMARY AND CONCLUSIONS

5-1 SUMMARY

Project Tugboat was a high-explosive, optimum depth-of-burial project done in coral overlaid with water and executed on the west coast of Hawaii in 1970. The original design of the project was based on throw-out cratering experience in wet, soft rock which had mechanical properties similar to the coral. The craters which resulted from the detonation of the 10-ton charges in the coral were wide, flat, and saucer-shaped instead of bowl-shaped, as expected. The volume was approximately four times larger than contemplated in the design, and apparently came entirely from crushing, compaction, and settling of the coral. This was verified by high-speed aerial movies of the cratering process, post-shot surveys of the craters, and post-shot seismic surveys of the material beneath the crater.

The earliest aerial high-speed movie view of the cratered area, once the steam and ejecta had cleared away, shows the existence of a conventional throw-out crater surrounded by a circular area of obviously crushed but still relatively intact coral. As the movie progresses, this crushed coral beyond the ejecta crater is observed to collapse and flow into the deeper center ejecta crater. The details of the process are then obscured as water flows back into the dewatered area and into the crater;

however, the final crater dimensions correspond to the radius of the crushed zone, as observed in the movie. The final crater is flat and saucer-shaped. There was no ejected material found above the original ocean bottom elevation, indicating that the entire volume had to come from a crushing, compaction, and consolidation process. The seismic surveys showed dipping beds beneath the cratered area, lending further support to the consolidation-compaction hypothesis as the mechanism for producing the crater volume.

The Tugboat experiments strongly suggest that the crater shapes and sizes observed in the PPG high-yield nuclear tests are due to the physical properties of the wet coral in which these tests were conducted. It is conjectured that the feature of wet coral sites which is responsible for their characteristic craters is the large, water-filled macroporosity of high permeability in a brittle coral matrix. It is proposed that, in the formation of craters in wet coral, the coral matrix is broken by the passage of the strong shock. The large macroporosity and high permeability then lead to a separation of grains and a consequent loss of strength.* In this state, the broken coral should flow easily. Finally, the broken coral matrix is expected to settle and compact to a state of reduced porosity.

The knowledge and understanding gained from Project Tugboat has been applied to the PPG craters since they are similar in shape and are in essentially the same material and environment. Since the cratering mechanisms apparently responsible for the final craters observed in

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* Although the exact nature of the process or processes involved is not known, some soil mechanics people would call the entire process described above liquefaction.

coral from an explosion are crushing and compaction, any process - direct coupling or air-overpressure - which deposits sufficient energy into the coral to accomplish this should produce similar results.

5-2 CONCLUSIONS

An analysis of the nuclear surface-burst craters at the PPG based on the information gained from Project Tugboat has led to the following conclusions:

- Crushing, compaction, and settling of the coral by the ground motion resulting from direct energy coupling and the high-pressure air blast could have formed the apparent nuclear surface-burst craters at PPG.

- Flat, saucer-shaped craters are due to the physical properties of the wet coral medium. The large crater volumes per ton of explosive are due to the large, water- filled macroporosity of the highly permeable brittle coral matrix.

- The shape and volume of the PPG craters are not related to the throw-out cratering phenomenon.

- Calculational techniques based on the throw-out approach to cratering and dry-land cratering experience should not be expected to replicate the PPG results.

- The average of 3.7 m^3/ton (130 ft^3/ton) cratering efficiency for the PPG craters equates to approximately 0.9 m^3/ton (32 ft^3/ton) for craters in equivalent strength dry-land material, if the same volume ratio for high-explosive cratering (coral overlaid with water to equivalent strength material on dry land) holds for nuclear, surface-burst results.

SECTION 6

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